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Fuel Cell Air Independent
Propulsion of Submarines

Peter L. Mart and
Jenny Margeridis

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Peter L. Mart and Jenny Margeridis

**Ship Structures and Materials Division
Aeronautical and Maritime Research Laboratory**

DSTO-GD-0042

ABSTRACT

Conventional diesel-electric submarines must surface periodically to recharge their batteries by using generators driven by air breathing diesel engines. During this time, submarines are most vulnerable to detection. Air independent propulsion (AIP) systems are being developed that will generate electrical power while the submarine is submerged. Such systems provide power for recharging the batteries, for propulsion and for the submarine's other electrical equipment requirements, while the submarine is submerged. Fuel cells, one of the leading AIP contenders, are electrochemical energy converters that enable the chemical energy of a stored fuel and an oxidant to be converted directly to electricity.

This Report reviews the main operational requirements of AIP systems in diesel-electric submarines, with the main objective of surveying the various types of fuel cell systems and ranking them in order of suitability for possible future use as AIP systems in the COLLINS Class submarine. Descriptions are given of the six fuel cell types currently in use or under development for terrestrial power generation, but particular attention is given to those systems that are in use or have the greatest potential for sub-sea applications.

The particular advantages of fuel cells compared with heat engines are highlighted, as well as the limitations imposed by fuel requirements. It is emphasised that for submarine AIP applications, there is no single optimum selection of fuel cell system, or of the fuel and oxidant and their associated storage and reactant processing systems. Each submarine application must be assessed on the basis of a number of different, and sometimes competing, criteria which will be weighted differently for different applications and strategic scenarios. It is concluded, however, that low temperature fuel cells are generally better suited for submarine applications, with the solid polymer electrolyte fuel cell having particular advantages.

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Executive Summary

The acquisition of six Collins Class submarines for the Royal Australian Navy (RAN) is a major investment, and considerable effort has been spent to ensure that the most modern technology is incorporated at build, with potential for ongoing maintenance and upgrading throughout the useful lifetime of these submarines, well into the next century. These conventional diesel electric submarines are currently the most advanced in the region, and possibly the world, but developments in submarine technology will erode this technological edge, unless similar modifications are incorporated into the fleet, either at build or during periodic maintenance or refit.

Conventional diesel-electric submarines are most vulnerable to detection and possible attack when surfaced, due to visible, infra red and radar signatures. The infra red signature is enhanced when the submarine's diesel engines are operational, as is the acoustic signature. A diesel-electric submarine needs to surface periodically to run its diesel powered generators in order to recharge its batteries, and this increases its vulnerability to attack by surface vessels and aircraft. Conversely, a submarine which has a reduced requirement to surface, and is more free to choose the timing and location of surfacing, has a significant tactical advantage. Nuclear submarines aside, the technology now exists to release the submarine from its enforced reliance on periodic visits to the surface. This Air Independent Propulsion (AIP) offers the opportunity to maintain the technological edge of the new Collins Class submarines, or to significantly erode that superiority if adopted by potentially hostile forces.

There are about six competing AIP technologies, at various stages of development. This Report specifically examines fuel cell systems, which are one of the three more advanced technologies. Stirling engine technology is also under active examination at AMRL, as are developments in closed cycle diesel technology. It is not the aim of this paper to compare the relative merits of these different technologies, which is done elsewhere. The field of fuel cell technology is much broader in existing scope, applications and development potential than either of the competing technologies, which are both relatively mature and targeted at niche applications in the military and subsea market, with little other application.

This Report reviews the main operational requirements of AIP systems in diesel-electric submarines (which are common to all competing technologies), and then surveys the various types of fuel cell systems, and assesses them against the AIP requirements. Development is rapid and ongoing in all areas of fuel cell technology, and this Report presents a view which is based on current developments to late 1994.

An attempt has been made to indicate the relative technological maturity of the different fuel cell technologies, which is important if a decision is required for forward planning and adoption of fuel cell technology by a specified time. Leadtimes for implementation of any AIP technology will depend on which technology is chosen, and whether the technology is to be incorporated into a new submarine at build (already too late for the current procurement of six Collins Class submarines), or at refit. Consideration has been given in the past to acquisition of further Collins Class submarines beyond the current six, and although this is not currently planned, the groundwork must be laid whereby such a decision could enable incorporation of AIP technology at build.

The leadtime requirements are less stringent if a decision is made to install AIP technology at refit. This allows more time for less technologically mature technologies, such as fuel cells, to develop. Therefore, with no current clear direction as to the likely course of any possible introduction of AIP into RAN submarines, it is also considered prudent to discuss some relatively immature fuel cell technologies. Areas are highlighted where there are currently fundamental scientific or materials problems which, if resolved, would enable rapid development to an engineered product.

Ramifications of the installation of fuel cell AIP technology into submarines are highlighted, particularly in the areas of fuel storage and processing. These are generally more complex than for other AIP systems which are able to use diesel fuel (though generally of a higher purity than currently used in air breathing diesel engines in submarines). It is emphasised that the fuel cell AIP system must be considered as a whole, and that the optimum choice of fuel cell and reactant storage and processing will depend on the particular application. However, it is concluded that the low temperature solid polymer electrolyte fuel cell shows particular advantages for submarine AIP. This is a proven technology undergoing rapid development for terrestrial applications (and even atmospheric/space applications), and is the fuel cell system of choice for AIP implementation by both the Federal Republic of Germany and Canadian navies.

Whatever decision is eventually made about the possible incorporation of some form of AIP technology into Australian submarines, it is certain that the RAN will be sharing the underwater environment with submarines of other navies equipped with AIP. An understanding of the capability of such systems, and the dramatic impact they will have on underwater warfare and tactics, will be vital to the maintenance of the superiority, and possible survival, of RAN submarines. It is hoped that this Report will further informed discussion on the ramifications of this new technology.

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1. Introduction

Submarines when submerged are vulnerable to detection by a wide range of sensors and increasing efforts are being directed to reduce submarine signatures. This encompasses both emanations from the submarine itself (acoustic, electromagnetic) which may be detected by passive detectors (sonar, pressure sensors, magnetic sensors) and by reflections off the submarine (active sonar). Signature reduction techniques include the use of anechoic coatings, magnetic signature reduction through degaussing and use of low magnetic steels, and noise and vibration abatement programs. These measures apply to conventional diesel-electric (SSK) and nuclear (SSN) submarines alike.

However, diesel-electric submarines have a fundamental limitation compared with nuclear submarines, because they recharge their batteries by using air-breathing diesel engines. This involves surfacing or snorkelling at periscope depth, which leads to a high probability of the submarine being detected from the surface or the air. Visual and radar detection of the above water submarine structures, acoustic detection of the diesel engines and exhaust, and infrared emissions are additional to the means of detection of a submerged submarine. While these can be reduced through use of radar absorbing coatings, and dispersal of the exhaust underwater, the submarine is nonetheless more vulnerable to detection than when submerged. The indiscretion ratio is defined¹ as the ratio of the time spent charging the submarine batteries (at the surface), to the time elapsed for the complete discharge/charge cycle of the batteries. In a typical diesel-electric submarine of about 2000 tonnes displacement, travelling at a speed of 6 knots, the indiscretion ratio is about 10%², and increases rapidly with increasing speed.

Air Independent Propulsion (AIP) involves carrying supplies of fuel and oxidant which are reacted in an energy conversion device to ultimately produce electrical energy. This is used primarily for propulsion and to power all electrical equipment. Since this can be carried out underwater, it offers the potential to reduce the indiscretion ratio and to enhance submerged performance by extending the underwater range and endurance of the submarine at low patrol speeds (typically 4 to 5 knots). While it is possible to recharge the submarine's batteries using AIP, the low power of typical AIP systems relative to the diesel-powered generator capacity would necessitate an inordinately long time to recharge a deeply discharged battery. It would also not be optimal use of the stored reactants, as there are inefficiencies in storing electrical energy in batteries for later use. AIP is best used in minimising discharge of the submarine's batteries, thus deferring conventional diesel engine recharging to a time and location suitable for the mission and strategic circumstances.

There are several AIP technologies at various stages of development worldwide. Heat engine systems include closed-cycle diesel engines, Stirling engines, closed-cycle gas turbines, and Rankine engines powered by hydrocarbon fuel (French MESMA system) or a small nuclear reactor (Canadian AMPS system). Fuel cells and semi-cells are the only non-heat engine technologies under development, other than development of high energy density batteries such as lithium aluminium iron sulphide (LAIS)¹⁰.

However, as batteries contain their reactants internally, they have a finite capacity unlike AIP systems whose endurance is limited mainly by the amount of reactants (fuel and oxidant) that can be carried. There are numerous literature reviews outlining and comparing the different systems^{2,3, 4, 5, 6, 7, 8, 9, 10,11,12}.

At AMRL, two of these AIP technologies, the Stirling engine and the fuel cell, are being investigated, to establish a technology base and the relative merits and disadvantages of both systems. Progress in the other AIP technologies is also being monitored, with a view to possible future introduction of AIP technology into the new Collins Class submarines if strategic circumstances dictate^{13,14}.

The main objective of this paper is to survey the various types of fuel cell systems, and rank those most likely to be suitable for AIP in the Collins Class submarine. The principle of operation of a fuel cell, and the different types, will be detailed in Section 3. For now, it is sufficient to note that a fuel cell is an electrochemical device that converts the chemical energy of two reactants, a fuel and an oxidant, into direct current electricity.

2. AIP and Submarine Operational Requirements

Both AIP technologies that are being evaluated at AMRL would be used in a hybrid configuration with the diesel engine in order to provide a secondary power source of about 300 to 600 kW. Hydrodynamic calculations¹⁵ on the Type 2400 submarine, of somewhat smaller size and mass than the Collins Class, show a propulsive power requirement at 4 to 5 knots of about 50 kW. The hotel load (all non-propulsive power requirements) is typically 100 to 200 kW in modern conventional submarines¹⁵. Therefore the AIP system must provide a minimum power of about 200 kW to operate the submarine at low patrolling speeds and provide the auxiliary electrical power (air-conditioning, navigation, weapons systems etc.) while "floating" the batteries at a constant level of charge. Sustained higher patrol speeds (e.g. greater than 6 knots) will deplete the battery charge unless an AIP system of higher power is installed. A system in the range 300-1000 kW would allow higher patrol speeds, and although of significantly lower power than the diesel generators (with a combined electrical output of more than 4 MW on the Collins Class¹⁶), would allow slow submerged recharging of a partially depleted battery, with zero indiscretion ratio. The higher powers would also augment significantly the high speed "sprint" endurance of the submarine battery. These issues are addressed more fully elsewhere¹⁷.

The required endurance of an AIP system would depend on the mission scenario. Calculations have been made² for a submarine of 2200 tons displacement with an AIP system of 250 kW, which will permit a maximum underwater speed of 6 knots (without discharging the battery). For an endurance of 15 days, this requires sufficient reactants to generate 90 MWh of electricity. This endurance is stated to be over five times the endurance obtainable by means of a typical submarine's battery alone. These

numbers may be used as a guide to the requirements and capacity of a practical AIP system for 2200 ton vessels.

With the state of development of current AIP systems, it is envisaged that first generation systems will comprise hybrid systems with the AIP system supplementing or partially replacing the existing diesel-electric/battery capacity. A submarine purpose-built to include AIP would disperse the various elements of the system throughout the submarine together with the existing diesel-electric/battery systems. These integrated systems would achieve optimal utilisation of space, and allow correct trim of the submarine. Dispersed systems can also reduce vulnerability, particularly when redundant systems are incorporated.

Where an existing submarine or design is to be retrofitted with AIP, as would be the situation for the Collins Class, the constraints are far greater than in a purpose-built AIP equipped submarine. The Collins Class submarines as designed have insufficient space to install an AIP system within the pressure hull and maintain the existing battery capacity. The first possible approach would be to replace one of the battery banks and possibly one of the three diesel generators with an AIP system. This would impose severe limitations on available space, limit the underwater sprint endurance of the submarine, and markedly increase the indiscretion ratio due to the reduction in diesel-electric generation capacity. This approach is thought to be operationally untenable.

The second more flexible approach is to design an add-on section or "plug", containing the entire AIP system. This would involve cutting the body of the submarine in two, and welding in the insert section, which would typically be about 10 to 15 m long, for a hydrogen/oxygen fuel cell system with 100 MWh of stored reactants installed in a Collins Class submarine¹⁷. At these endurances, the mass and volume of reactants primarily determine the size of the plug, with the size of the AIP energy converter and subsystems being of secondary importance. For the same fuel (eg diesel) and endurance, the higher oxygen requirement of heat engines compared to fuel cells would necessitate larger oxygen storage requirements, and therefore a longer plug. Nevertheless, different methods of hydrogen storage or generation can have a substantial effect on the resultant plug length¹⁷, somewhat diminishing the oxygen advantage of fuel cells over other AIP systems. Figure 1 shows a schematic of an AIP plug inserted in the Collins Class submarine, although for realistic endurances the relative size of the reactant storage tanks would be much greater than that shown.

Such an operation has been successfully carried out with the German Type 205 submarine *U1* on two occasions. In 1987 fuel cell AIP plant was installed, and underwent nine months of successful sea trials. Following decommissioning in 1992, closed cycle diesel AIP plant was installed prior to two months successful sea trials in early 1993. The Swedish submarine *Näcken* (A14 Class) was also cut in 1987 for installation of the Stirling engine system, with four months successful sea trials in 1988/89, and subsequent continuous operational deployment⁴.

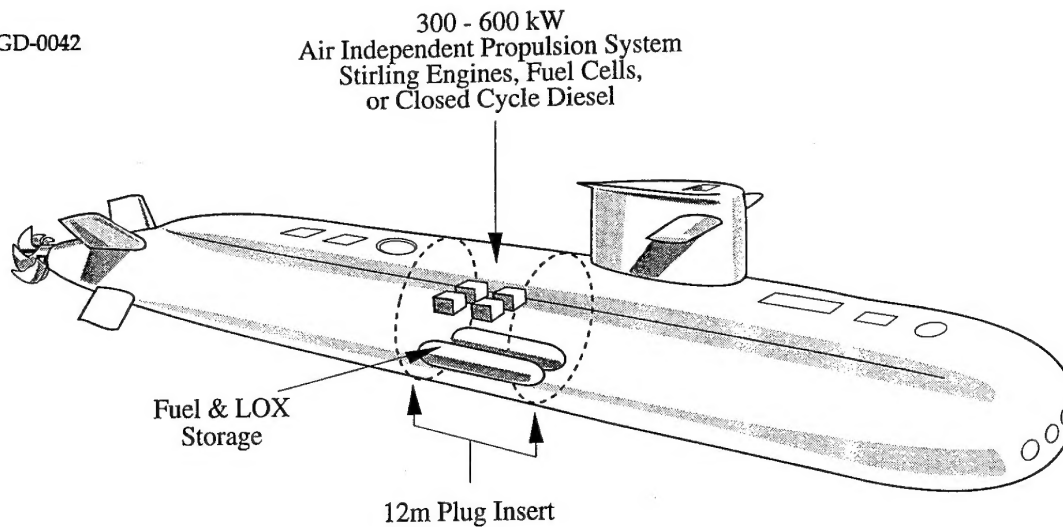


Figure 1 Schematic Air Independent Propulsion in Collins Class Submarine

There are a number of very important factors which have to be considered in the selection of a submarine AIP system. These factors (discussed below) are often inter-related and compete with each other, so the relative weighting given to each will depend on the strategic and operational requirements.

2.1 Efficiency

The efficiency of an AIP system is defined as the ratio of the output electrical energy to the energy content of the input reactants. High efficiency is important in minimising the fuel and oxidant consumption, enabling maximum underwater range and endurance, and minimal length of the inserted plug. The length of the plug determines the handling characteristics of the submarine; a longer plug will increase the turning circle, impose greater stresses on the hydrodynamic control surfaces, and reduce the maximum underwater speed of the submarine. The more efficient the AIP system, the less the heat that has to be exhausted overboard in cooling water. This has importance in reducing the infrared signature of a submarine loitering near the surface, although it would be less important for a submarine patrolling at depth, where mixing of the exhausted hot water would rapidly dissipate the thermal signature. Lastly, the cost of fuel and oxidant will also be reduced with a more efficient system, although this would probably be a minor consideration compared with the above issues.

2.2 Signature

An AIP system must have low detectability and not compromise the low signature of the diesel-electric submarine operating on battery power alone, through either acoustic noise, electromagnetic emanations (including infra-red), or exhaust products. An electrochemical system, with no moving parts, is inherently quieter than a system which converts the chemical energy of reactants to heat, then to mechanical energy and finally to electrical energy. Structure-borne and air-borne acoustic noise and vibration

can be reduced by isolating sources from the submarine hull. However, reduction at the source will minimise the need for such measures, which all take up vital space.

An AIP system using an hydrocarbon fuel produces a carbon dioxide exhaust which must be either stored on-board, through mechanical compression and liquefaction, or chemical scrubbing, or it must be disposed of overboard, against the ambient seawater pressure at the operational depth. Storage of liquid CO₂ in the LOX tanks, as proposed by Kumm¹⁸ would eliminate the exhaust, and the need to compensate the mass change of the submarine with seawater. Chemical scrubbers are very effective for removing carbon dioxide from exhaust gases, but are generally non-regenerative and require a large onboard inventory of chemicals, and take up valuable space. Seawater scrubbers are less effective than chemical scrubbers, since carbon dioxide is only sparingly soluble in seawater¹⁹. A system jointly developed by Newcastle University (UK) and Carlton Deep Sea Systems (formerly Cosworth Deep Sea Systems) uses a CO₂ absorber and a water management system to dispose the CO₂ laden water overboard. However, the system imposes a 10 to 15% power drain on the system²⁰, which decreases the AIP performance.

Since sea pressure increases by one atmosphere for every ten metres of depth, and the suggested diving depth of the Collins Class submarine is 300 metres²¹, an AIP system must operate at greater than 30 bar pressure to be truly depth independent, or must use supplementary pumps to pressurise its exhaust to the ambient seawater pressure. The dissolved carbon dioxide must not come out of solution when pumped overboard, as a trail of bubbles at the surface would readily give away the position of the submarine, and may also produce acoustic noise discernable on passive sonar.

2.3 Performance

The performance of an AIP system is important in maximising the operational and strategic benefits. High specific power density, both gravimetric (kW/kg) and volumetric (kW/m³), is desirable to ensure the maximum power output from the minimum size plant. Although for reasonable range and endurance, the mass and volume of reactants will be far greater than the mass and volume of the AIP energy converter, reduction in the size of the latter will contribute to a more compact overall system, and hence a shorter plug length. High efficiency across the whole range of output power is desirable, and maximum efficiency should preferably occur at the load factor at which the system is designed to usually operate. Performance should not deteriorate with time. The AIP system should have rapid startup, and good load-following characteristics, with the ability to handle transient overloads.

2.4 Reliability

The reliability, availability and maintainability of the AIP system is most important for submarine applications. There should be a low incidence of component failure, a long mean time between overhauls, and the system should be easily maintained and

repaired at sea. Modular systems confer advantages over a single system, because if a single system fails, the whole of the rated power is made unavailable, whereas if one of a number of smaller modules fails, only its proportion of the rated power is unavailable. Modular systems also allow the possibility of module replacement at sea, with replacement of the defective module by a spare, and repair carried out either at sea or on return to port. Obviously this is only feasible with relatively small modules.

2.5 Safety

Safety is very important in the confines of a submarine, where the effects of fire or explosion are potentially catastrophic. Safe storage and handling of the reactants and byproducts should minimize risk to personnel and the submarine itself. The AIP system including reactant storage and any reactant processing sub-system must also be resistant to shock, particularly for storage of cryogenic fluids such as liquid oxygen (LOX). There is some accumulated experience with the safe usage of LOX in submarines²², with the Swedish Navy having safely operated inboard LOX tanks on the *Näcken* for over five years, and German experience with an external LOX tank on the Type 205 *U1* in fuel cell and closed cycle diesel trials. Both Sweden and Germany have shock tested their LOX tanks. Spillage of cryogenic liquid is also a concern if it contacts the hull, and embrittles it. The Swedish system uses an insulated "cold box" to contain any spillage from valves or pipes, whereas the German system uses non-magnetic steel, which is stable at low temperatures, for both the hull and LOX tanks.

Long term exposure to air-borne contaminants introduced by an AIP system would be a cause for concern, particularly if these are toxic. Much greater attention is paid nowadays to the long term effects of continuous exposure of submariners to their working environment. Effective removal of air-borne contaminants is necessary to prevent chronic exposure to low levels of different chemicals that may eventually lead to health problems. In this respect, AIP systems reduce the necessity of the submarine to snorkel in order to recharge its batteries, and thereby reduce the ingress of diesel fumes into the submarine atmosphere, as well as increasing crew comfort. (When the air mast of a snorkelling submarine submerges in waves, the diesel engine draws air from the submarine atmosphere, which causes rapid and uncomfortable pressure fluctuations). The issue of crew comfort could be particularly important in a high sea state, where the discomfort of the crew of a snorkelling submarine could lead to fatigue, which may induce unsafe operation.

As with all submarine systems, safety must be designed into the system and operating procedures so that a relatively minor component failure cannot cause a chain of events that eventually threatens the survival of the submarine and crew. Risk assessment becomes highly specialised when dealing with complex AIP systems on board a highly complex platform such as a submarine. Techniques such as failure mode and criticality analysis, and fault tree analysis, if rigorously applied from the outset, should give submariners confidence that introduction of an AIP system will not compromise existing safety standards.

2.6 Systems Compatability

The AIP system must be compatible with the existing submarine propulsion system, particularly the electrical system and batteries. Since the batteries charge and discharge by direct current, an AIP system must produce direct current either by an electrochemical reaction, by a dc generator, or by an ac generator and rectifier. The AIP system output voltage must also match the bus voltage of the batteries and propulsion motor, across the applicable power range. For systems that produce direct current electrochemically, this may require appropriate series and parallel electrical connections, to achieve the desired voltage and current, or the use of dc to dc inverters, to maintain a particular output voltage from a varying voltage source. The system must also be tolerant of or protected from voltage transients (back emf) caused by changes in the load on the inductive propulsion motor.

There are particular constraints in a submarine on mass (which affects buoyancy) and mass location (which affects trim). There is also a volume limitation due to the limited length of an insert hull section which can be retrofitted to an existing submarine, before the handling characteristics and power requirements are adversely affected. In practice, a retrofitted AIP plug insert must be neutrally buoyant so as not to affect the overall buoyancy of the submarine. However, if an AIP system can be designed as an integral part of the submarine at build, it should be possible to share some subsystems, such as heat exchangers, with the existing diesel-electric systems.

2.7 Logistics and Costs

The proposed reactants to operate the system should be logistically feasible. This includes on-shore and at-sea bunkering, which should preferably be compatible with existing fuels in Navy use. Replenishment, usually in port, but possibly at sea, should be easy, and would most easily be accomplished for liquid fuels. Cryogenic fuels or LOX would be considerably more difficult to replenish at sea. Separate storage requirements for non-diesel fuels will complicate storage on a submarine, particularly if the fuels are miscible with seawater, or uptake undesirable sulphur (in the form of sulphate salts) which may induce hot corrosion problems in some heat engines. The use of dedicated storage tanks or bladders to separate the fuel from seawater ballast would be necessary. If a fuel requires further on-board processing before it can be used in an AIP system, that increases the complexity of the system. It also has the potential to detrimentally influence all the above mentioned factors of efficiency, performance, reliability, signature, safety, systems compatibility, and also the overall cost.

The cost of any retrofitted AIP system will be substantial, given that it involves removing a submarine from active service for a considerable period of time, cutting it in two, inserting the AIP autonomous plug and reconnecting through services, and rewelding the submarine. It is not the purpose of this paper to compare the different AIP technologies, but in each case the overall cost must be balanced against the strategic and operational benefits gained. Overall cost must consider both purchase cost and through-life costs, the latter including the downtime costs of periodic

maintenance and repair, spares, and reactant costs. Since the different technologies are at different stages of development, and very few units of those currently operational have been sold, unit costs are high and include the amortisation of the research and development costs. Furthermore, the economy of scale offered by markets for non-military applications may rapidly change the relative purchase costs of different AIP technologies. It is therefore difficult to currently predict the overall costs of the various AIP technologies at some time in the next decade, when the situation may have substantially changed.

3. Fuel Cell Principles

Fuel cells directly convert the chemical energy of the reactants, a fuel and an oxidant, into direct current electricity. Fuel cells will continue to operate for as long as the externally stored reactants are supplied. The fuel cell system includes the fuel cell stacks and control systems, the stored fuel and oxidant, storage vessels, associated pipework and reactant processing systems, and exhaust product handling system.

Commonly used reactants include air and oxygen as the oxidant and pure hydrogen or hydrogen derived from catalytically reformed hydrocarbons or cracked ammonia as the fuel. Hydrazine has been used in military fuel cells, and methanol has been used as a liquid fuel in the direct methanol fuel cell.

The fundamental components of the fuel cell are the porous gas diffusion electrodes, comprising the fuel electrode or anode and the oxidant electrode or cathode. These two reaction sites are separated by an ion conducting electrolyte which can be either a liquid, a liquid immobilised on a porous substrate, or an ion conducting solid. The conductive electrodes are connected electrically through a load (e.g. electric motor) by an external circuit. At the anode, oxidation of the incoming fuel produces electrons, which provide power in the external load, and then reduce the incoming oxidant at the cathode. A flow of ions through the electrolyte completes the circuit. This is shown schematically in Figure 2, for a number of different types of fuel cells. The most common fuel cell is the hydrogen/oxygen fuel cell, with either an acidic or an alkaline electrolyte. In an acid electrolyte fuel cell, the conducting ions are protons produced at the anode, and water is the reaction product at the cathode. In an alkaline electrolyte fuel cell, hydroxide ions are produced at the cathode, and the water reaction product is produced at the anode.

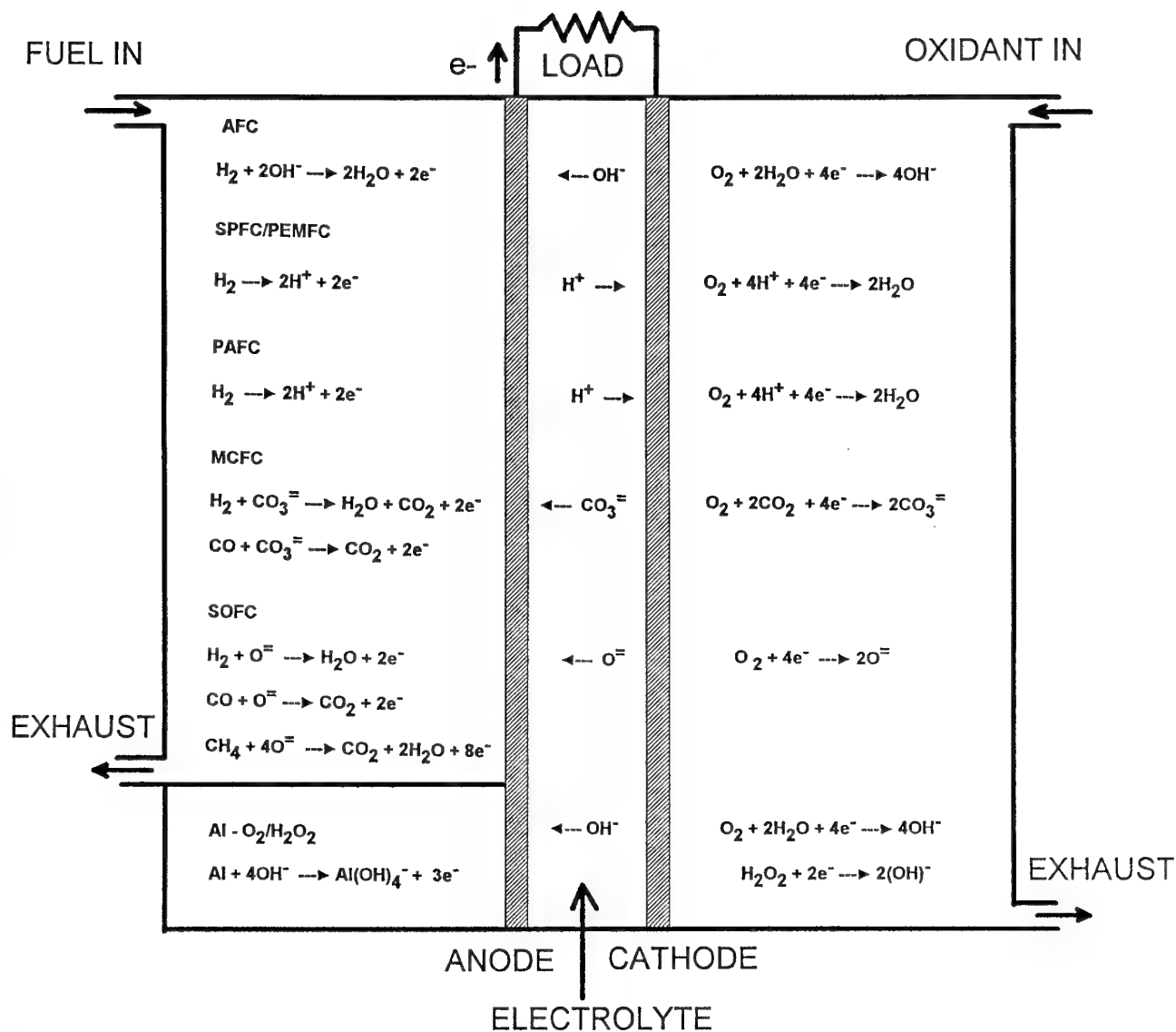


Figure 2 Schematic representation showing the electrochemical reactions occurring with different fuels and oxidants in a number of fuel cell types.

AFC: Alkaline Fuel Cell

SPFC/PEMFC: Solid Polymer Fuel Cell / Proton Exchange Membrane Fuel Cell

PAFC: Phosphoric Acid Fuel Cell

MCFC: Molten Carbonate Fuel Cell

SOFC: Solid Oxide Fuel Cell

Al - $\text{O}_2/\text{H}_2\text{O}_2$: Aluminium-oxygen semi-cell

In low temperature fuel cells, catalysts impregnated into the porous gas diffusion electrodes are required to promote these reactions, whereas in high temperature fuel cells the kinetics are generally sufficiently fast that catalysts are not required.

Individual fuel cells connected in series (generally in a planar arrangement) form a fuel cell stack. The individual cells are connected by a ribbed bipolar plate that provides low electrical resistance between adjacent porous cathode and anode structures and also functions as a gas barrier between the fuel and oxidant streams in the adjacent cells. This is shown in Figure 3.

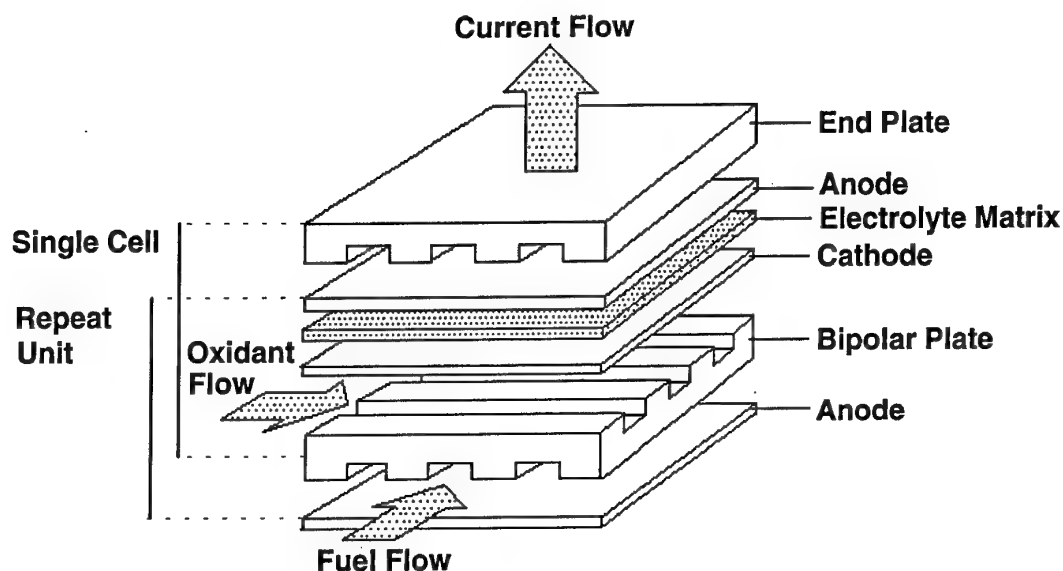


Figure 3 Planar arrangement of fuel cell components (after Steele²³)

By connecting a multiplicity of stacks it is possible to form a fuel cell of any desired voltage and current output. In low temperature fuel cells, the design must also facilitate removal of the water product from the stack to prevent flooding of the electrodes which may block the gas flow.

Since the fuel cell is an energy converter, ideally no part of it should undergo any irreversible chemical changes. In reality, there are intrinsic losses which result in the cell potential deviating from the ideal cell voltage exhibited at equilibrium. These losses are referred to as polarisation losses and there are three factors contributing to the overall cell performance:

1. Activation polarisation is related to the energy barrier that must be overcome to initiate a chemical reaction between reactants. Activation polarisation predominates at the cathode where the oxygen reduction kinetics are slow.
2. Ohmic polarisation is due to electrical impedances occurring within the electrodes and ionic impedances within the electrolyte.

3. Diffusional polarisation occurs when the electrode reaction is inhibited by the inability of the reactants and the products to diffuse rapidly to, or away, from the reaction site.

The activation losses are predominant at lower current densities while the ohmic and diffusional polarisation losses are prevalent at high current densities. So, by fine tuning the components at the critical sites where these losses occur, higher power densities can be attained.

4. Types of Fuel Cells

Table 1 lists the six main types of fuel cells^{24,25,26} which are classified according to their electrolyte, and more generally grouped together on the basis of their operating temperature.

Table 1: Operating Characteristics of Fuel Cells

Fuel Cell Type →	AFC	SPFC	Al/O ₂	PAFC	MCFC	SOFC
Electrolyte	Liquid KOH	Solid polymer	Liquid KOH	Liquid H ₃ PO ₄	Molten (Li,K) ₂ CO ₃	Solid zirconia
Temperature (C)	50-90	70-80	50-60	190-210	600-700	800-1000
Stack Startup Time	Rapid	Rapid	Rapid	Moderate	Slow	Slow
CO ₂ Tolerance	Low	High	N/A	High	High (reactant)	High
CO Tolerance	Low	Low	N/A	Low	High	High
Power density	High	High	Low	Low	High	High
System Electrical Efficiency (%HHV)			50			
(H ₂ /O ₂)	55-65	50-60	N/A	45-55	45-55	45-55
(methanol/O ₂)	40-50	40-50	N/A	40-45	45-55	-
(methane/O ₂)	-	-	N/A	40-45	50-60	50-60
Reforming hydrocarbons	External	External	N/A	External	Internal	Internal

AFC: Alkaline Fuel Cell SPFC: Solid Polymer Fuel Cell Al/O₂: Aluminium-oxygen semi-cell
 PAFC: Phosphoric Acid Fuel Cell MCFC: Molten Carbonate Fuel Cell
 SOFC: Solid Oxide Fuel Cell N/A : not applicable HHV: Higher Heat Value

Table 2, although by no means exhaustive, illustrates the relative technical maturity of the different types of fuel cell.

Table 2: Development Status of Fuel Cells

Fuel Cell	Technology Status	Country/Company, Research Lab. /Funder	Remarks
AFC	Mature	Belgium/Elenco Germany/Siemens Japan/Fuji Electric USA/Pratt & Whitney Div. of UTC	24-cell (450 W) modules, 1-70 kW stacks, 80 kW bus under development with Ansaldo 16x6 kW stacks in "U1" sub., (1989) 7.5 kW space shuttle 3x12 kW
SPFC	Early to Mid Development	Canada/Ballard Ballard/(DND) Germany/Siemens Italy/De Nora USA/Billings USA/Energy Partners USA/Ergenics Power Systems USA/Hamilton Standard Div. of UTC USA/H Power USA/International Fuel Cells/(ARPA) USA/Los Alamos Natl. Lab. USA/Texas A&M Univ.	35-cell, 3-5 kW (H ₂ /air), 10 kW(NG), 120 kW (24 x 5 kW) stacks in bus 40 kW demonstrator for UUV/submarine by 1996 72-cell, 34 kW (H ₂ /O ₂) 40 kW bus under development with Ansaldo 17.5 kW (unconfirmed) 25-cell 5 kW (H ₂ /O ₂), 60-cell 5 kW (H ₂ /air) 1.5 kW (discontinued) substantial water electrolyser experience 10 kW 12 kW for UUV applications fundamental & applied research " " " "
AI/O ₂	Early Development	Canada/Alupower Alupower/(DND) USA/Eltech, Loral/(ARPA)	600 W- 6 kW telecommunications, 40 kW demonstrator for UUV/submarine by 1996 15 kW for UUV applications
PAFC	Mature, Commercial	Italy/Ansaldo, International Fuel Cells Japan/Fuji Electric Corporation Japan/Hitachi Japan/Mitsubishi Electric Mitsubishi Electric/(NEDO) Japan/Sanyo Electric Japan/Toshiba USA/Engelhard USA/H Power, Fuji Electric/(DOE) USA/International Fuel Cells (IFC: UTC & Toshiba) USA (IFC)/Italy (Ansaldo) USA-Japan/ONSI (subsidiary of IFC) USA/UTC USA/UTC/(EPRI) USA/Westinghouse, Energy Research Corp./(DOE)	1 MW, external reformer (NG), on-line 1992 23(+4) x 50 kW, 10(+5) x 100 kW, 2(+1) x 500 kW (NG/LPG), 200 kW (methanol), 5MW (NG) in '95 100 kW (NG) 100 kW (methanol) 200 kW (NG) 220 kW (NG) 2(+6) x 200 kW 50 kW (methanol) methanol fuel, 50 kW bus (55 kW stack) (1994) 4.5 MW, 11 MW (1991) 1 MW (1993) 200 kW, 56 ordered in 11 countries (1993) 65x12.5 kW, 46x40 kW 4.5 MW 100 kW stack tested, 375 kW module due 1992
MCFC	Mid Development	Italy/Ansaldo Japan/Fuji Electric/(NEDO) Japan/Hitachi/(NEDO) Japan/Ishikawajima-Harima Heavy Industries/(NEDO) Japan/Mitsubishi Electric(NEDO) Japan/Toshiba/(NEDO) Netherlands/Brandstofcel Nederland USA/Energy Research Corp./(EPRI) USA/M-C Power/(DOE,EPRI,GRI)	100 kW (1994) 10 kW 10 kW, 25 kW, 100 kW (4 x 25 kW) 10 kW, 100 kW, 1 MW internal reforming (NG) (1992-96) 5 kW internal reforming NG, 100 kW (NG) 10 kW 50 kW (NG, 1994), 2 x 250 kW (coal gas, 1995) 7 kW, 20 kW, 100 kW internal reforming (NG) internal reforming (NG), 250 kW- 500 kW modules planned

Table 2: Development Status of Fuel Cells

Fuel Cell	Technology Status	Country/Company, Research Lab. /Funder	Remarks
SOFC	Early Development	Australia/Ceramic Fuel Cells Ltd. CEC/Asea Brown Boveri, ICI, British Gas, Riso Nat. Lab. (Denmark), TNO (Netherlands) CEC/Siemens (FRG), General Electric (UK), Imperial College (UK) Japan/Electrotechnical Lab. Japan/industry (various) USA/Argonne Natl. Lab. USA/Westinghouse Elec./(DOE)	100 W, 5 kW (by 1997) developing 1 kW stack (1992) developing 1 kW stack (1992) 500 W, 10 kW planned testing Westinghouse stacks, R&D R&D monolithic SOFC 3 kW, 20 kW, 25 kW developed 100 kW (1994)

ARPA: Advanced Research Projects Agency

DND: (Canada) Dept. of National Defence

DOE: Department of Energy

EPRI: Electric Power Research Institute

GRI: Gas Research Institute

LPG: Liquid Petroleum Gas

NG: Natural Gas

NEDO: New Energy and Industrial Technology Development Organization

UTC: United Technologies Corp.

UUV: Unmanned Underwater Vehicle

4.1 Low Temperature Fuel Cells

For the purpose of this paper, low temperature is used to describe fuel cells for which it is not possible to use the waste heat to produce steam for hydrocarbon fuel reforming. Low temperature fuel cells generally require relatively pure O_2 and H_2 gases and are easily contaminated by impurities. They usually require high loadings of noble metal electrocatalysts because of the slower electrode kinetics at low temperatures. Hydrocarbon fuels must be reformed externally, with heat supplied for the endothermic steam reforming reaction, by burning fuel and/or waste hydrogen from the fuel cell. The low temperature fuel cells show a varied tolerance to carbon monoxide (CO) and carbon dioxide (CO_2) by-products of the reforming process, and these must generally be removed to prevent degradation of the electrolyte and/or poisoning of the catalyst.

It is interesting to note that a low temperature fuel cell, running on hydrazine hydrate and gaseous oxygen, was developed in 1964 by Allis Chalmers Manufacturing Company under contract to the Electric Boat Division of General Dynamics. This 750 W fuel cell system was used to power a one-man underwater research vessel, and is believed to be the first example of fuel cells used in a submersible or submarine²⁴. Low temperature fuel cells have been used as onboard electrical power supplies in the US space programs Gemini and Apollo and on the Space Shuttle, as they provide instantaneous high current densities.

4.1.1 Alkaline Fuel Cell

Information on the historical development of alkaline fuel cells (AFC) may be found in the extensive review by Bockris and Appleby²⁷. The present review concentrates on submarine applications.

ASEA in Sweden developed a 200 kW land demonstration alkaline fuel cell system (Victor) in 1964 for submarine application, under contract from the Swedish navy^{28,29,30}. The system contained twelve AQE batteries connected in series, each with a nominal output of 20 kW at 0.7 V and 200 mA/cm². Each battery contained four stacks in parallel, and there were twenty modules in series per stack, with each module containing eight cells (of electrode area 314 cm²) in parallel³¹. The system thus contained a total of 7680 cells. Ammonia was used as a fuel, and cracked catalytically to produce hydrogen for the fuel cell and nitrogen which was liquified and stored in empty sections of the liquid oxygen tank (to maintain submarine buoyancy). The complete system was run for 4000 hours, with high reliability of the fuel cells (mean time between failure was 400,000 hours³⁰, determined from extensive long term testing³²). However, a catastrophic fire occurred in 1967 due to a failure in the air supply to the pneumatically controlled oxygen valves. This caused a build up of oxygen pressure in the system, breaking electrodes and resulting in an oxygen fire which destroyed several stacks, exacerbated by the use of polymer frames. The project was subsequently abandoned. Prior to the accident, the first batteries in the system had accumulated 1200 hours of operation, and the average operating time for the batteries was 500 hours.

In 1978 Lockheed installed two United Technologies Corporation (UTC) 30 kW alkaline fuel cells on board the Deep Submergence Search Vehicle, *Deep Quest*, which made about 50 successful dives on fuel cell power^{33,34}. High pressure hydrogen and oxygen were stored at 200 bars in spherical steel pressure vessels. A 45% KOH electrolyte and an operating temperature of 120°C were used, and the efficiency was about 60%^{34,35}. Although technically satisfactory, the system was not adopted for the Deep Submergence Rescue Vessel (DSRV) due to different mission requirements, where batteries were more suited to recharging from the "mother ship" SSN³³.

More recent developments pertinent to AIP are discussed below, and the current commercial status of alkaline fuel cells and the maximum power available is summarized in Table 2.

Siemens in Germany have been active in the development of the low temperature (80°C) alkaline H₂/O₂ fuel cell since the mid-sixties. A feature of Siemens alkaline fuel cells is the use of cheaper electrode materials (Raney nickel anode, doped silver cathode) instead of platinum electrocatalysts³⁶. The fuel cell of active area 340 cm² with a mobile KOH electrolyte produces a current density of 400 mA/cm² at 0.8V cell potential. A 60 cell 6 kW fuel cell module was constructed, producing 48 V at 125 A, with an efficiency (based on the lower heating value of hydrogen) of 61-63% at rated load and a maximum efficiency of 71-72% at 20% load factor. This proved to be a reliable system with over 20,000 h of accumulated module operation³⁷ in a sixteen module 96 kW land based demonstration system. This was then installed on the

German Navy Type 205 submarine *U1*³⁸. The nine month sea trial in 1988-89 clearly demonstrated that this fuel cell propulsion system is modular and flexible with a high reliability, conferring operational and tactical advantages on submarine operation. Siemens is now developing a solid polymer electrolyte fuel cell system which promises better performance than that used in the *U1* (see Section 4.1.2).

The main advantage of the alkaline fuel cell is the enhanced cathode performance, as the oxygen reduction reaction is more rapid in alkaline electrolytes than in acidic electrolytes at low temperatures (<100 °C). The drawback commonly advanced for AFCs is that they are most susceptible to carbon dioxide in the reactants, as the electrolyte reacts with the CO₂ to form carbonates. This severely limits cell performance with reformed hydrocarbon fuels or air, and requires pure hydrogen as the fuel and pure oxygen as the oxidant. Although there are a number of proven technical solutions for removing CO₂, all involve an energy and cost penalty not imposed on CO₂ - tolerant systems. This offsets the enhanced performance of the AFC using pure reactants. Appleby²⁴ (pages 275-277) discusses how this has led to different approaches in Europe (which favours AFC) and the United States (which favours PAFC) for utility power generation using hydrocarbon fuel. Lindström³⁹ strongly rejects the "CO₂ syndrome" as an impediment to big AFC plants operating on fossil fuels, and points out that the technology for CO₂ removal is routinely and efficiently used in the ammonia industry.

Another disadvantage is that a mobile electrolyte needs to be recirculated for the removal of product water and waste heat from the fuel cell, which requires a complex system. However, Siemens has also developed an alkaline fuel cell with the electrolyte immobilised in a porous matrix such as asbestos³⁶, where the product water is removed as water vapour from the recirculating hydrogen, and waste heat by coolant circulation.

Significant improvements have been made in the technology of alkaline fuel cells for space applications, since the use of Pratt and Whitney high temperature, high pressure 1.5 kW fuel cell modules in the Apollo space program. Continued development of the Apollo system by UTC International Fuel Cells Division (the former Pratt and Whitney fuel cell group) produced the space shuttle orbiter fuel cell system, comprising three low temperature, low pressure 12 kW modules. The stack power to weight ratio increased by forty times to 0.5 kW/kg²⁴. In 1987, UTC developed an advanced lightweight alkaline system, with stack power and current densities of 24 kW/kg and 5 A/cm² respectively at 0.8V²⁴. These latter two systems use noble metal (Pt-Pd, Au-Pt) alloys for the anode and cathode respectively, and the electrolyte is immobilized in a thin reconstituted asbestos matrix, to reduce weight. The Apollo fuel cells did not require Pt catalysts, since the high temperature promoted rapid kinetics.

In the former U.S.S.R. the 10 kW "Photon" alkaline fuel cell was developed for space applications in 1984⁴⁰, with four stacks producing a net output power of 27 kW, at a specific power of 68 W/kg.

4.1.2 Solid Polymer Fuel Cell

The solid polymer electrolyte fuel cell (SPFC), also known as the proton exchange membrane fuel cell (PEMFC), was first developed by the General Electric Company and used in the 1 kW Gemini project with a cross-linked polystyrene sulfonic acid membrane. The life of the early membranes was limited by oxidative degradation.

Research in the early 1960's by Du Pont led to the development of Nafion[®], a perfluorosulfonic acid membrane. This was electrochemically stable at temperatures up to 100°C, and an excellent proton conductor. The membrane contains pendant sulfonic acid functional groups which readily undergo cationic exchange with protons. The membrane most commonly used for fuel cells is designated Nafion 117, having an equivalent weight of 1100 and a thickness of 175 µm. Considerable research into new membranes has resulted in better membrane performance.

In 1986 the Dow Chemical Company introduced a new experimental perfluorosulphonic acid membrane with a lower equivalent weight, and shorter pendant groups with a terminal sulphonic acid group⁴¹. This material exhibited higher ionic conductivity than the Nafion 117 membrane, and was used by Ballard Power Systems Inc. in Canada to achieve current densities in small SPFC stacks of up to 4.3 A/cm² at 0.5 V per cell, four times that produced by Nafion 117 at the same voltage⁴². The initial Dow membrane was very thin and difficult to handle⁴³. Experience at AMRL confirmed that the membrane expanded/contracted considerably in the membrane plane upon hydration/dehydration respectively. Later versions are reported to have improved in this respect.

More recently, Du Pont has produced thinner versions of Nafion 117, designated NE 112 and NE 115, and a more conductive polymer composition designated NE 105 5L. These give similar performance to the Dow membrane. Ballard has now developed its own advanced membrane for SPFC applications.

During operation of the fuel cell, water management is critical since the membrane must be maintained in a fully hydrated condition for maximum proton conductivity, yet flooding of the electrodes must be avoided. Water is introduced at both electrodes by humidifying the incoming gases, and the water produced at the cathode is removed with the exiting oxygen gas. This limits operation to temperatures below the boiling point of water at any given pressure.

The solid polymer fuel cell operates best on pure hydrogen gas, but is quite tolerant to carbon dioxide (such as is present in reformat gas), with only a slight reduction in voltage due to minor polarisation dependent on the concentration of CO₂. However, carbon monoxide present in reformat gas poisons the platinum catalyst in the anode and causes a dramatic decrease in cell performance, at concentrations as low as 10 - 100 ppm. It has been shown that CO poisoning can be eliminated by injecting oxygen at a level of 2-5% (O₂/H₂) at the feed anode inlet⁴⁴, which oxidises the CO to CO₂. Research into CO-tolerant electrocatalysts is also continuing at a number of laboratories.

Initially, high Pt catalyst loadings (typically 4 to 8 mg/cm²) were a drawback of the solid polymer fuel cell because of the cost. However, recent modifications to the design and composition of the electrodes have led to a major reduction in the cost of the fuel cell and better performance. By incorporating a proton conductor, such as Nafion, into the surface of an electrode containing low loadings of Pt catalyst, the same level of performance could be achieved as in electrodes containing ten times the Pt loading⁴⁵. At present, the major component cost of this fuel cell system is that of the membrane, rather than the platinum catalyst, and this cost is dropping as competitive membranes are developed and the market widens.

The solid polymer electrolyte offers a low maintenance electrolyte system that is free of the leakage often associated with liquid electrolytes, does not require replenishment, and is robust and able to withstand differential gas pressures. Manufacturers of commercial SPFCs and research laboratories at the forefront of SPFC research are listed in Table 2.

The history of SPFC technology for underwater applications dates back to the late 1960's, when General Electric (GE) developed two small power sources (1.8 kWh and 44 kWh) for the U.S. Navy for submerged buoy applications⁴⁶. In 1978 GE conducted a study (referenced in ⁴⁶) for the Canadian Defence Research Establishment for a 17 kW, 96 kWh power plant to provide propulsion, heating and emergency life support for a 13 tonne deep diving submersible. This was based on fuel cell stack technology developed by GE for NASA. They also reported a feasibility study of a 2.6 MW, 338 MWh power plant for a 1815 tonne submarine, based on 325 kW modules. They saw no problems in developing this size of fuel cell module, having successfully produced a 200 kW solid polymer electrolyte water electrolysis module. However, cryogenic storage of the reactants, which was stipulated as the baseline system, was found to be excessive in volume.

Hamilton Standard Division of United Technologies Corporation has over 35 years experience in the development of solid polymer electrolyte cells, primarily for water electrolyzers, but also as fuel cells. It is estimated that they have accumulated over 100 million cell-hours of experience⁴⁷. The SPE water electrolyser system is in use by both the U.K. Royal Navy and the U.S. Navy for oxygen generation on nuclear submarines⁴⁸. In the U.K. Navy, over 41,000 operational system hours have accumulated without a single malfunction, with the longest operational service for any single electrolyser module more than 8500 hours as at the end of 1990. During development and subsequent operation of the electrolyser systems, over 8 million cell hours have been accumulated on the basic 0.23 ft² (0.021 m²) cell design. The U.S. Navy system in qualification testing was successfully shock tested in excess of 100 g while pressurised to 3000 psi (20.6 Mpa), and the cell module sustained no damage⁴⁷. The electrolyzers use robust Nafion 120 membrane and expanded sheet metal screen fluid flow fields, sheet metal separators, and individual cell compression pads for flexibility. This promotes long stable life, exceptional fluid sealing and high tolerance to shock and vibration.

Hamilton Standards has applied their successful electrolyser technology to solid polymer electrolyte fuel cells. They now own the technology developed by General

Electric (²⁴, page 146). They designed and built 1 ft² (0.093 m²) fuel cell hardware with molded carbon/graphite electrodes incorporating fluid flow fields. However, they considered them too inflexible and brittle for military use, where gas leakage or susceptibility to cracking due to shock and vibration would be a problem. Instead they developed sheet metal fuel cells of 0.78 ft² (0.073 m²) area, using Nafion 120 and 117 membranes. They achieved current densities of about 530 A/ft² (0.57 A/cm²) and 800 A/ft² (0.86 A/cm²) respectively at 0.6 volt in single cells (and also in a 3-cell stack using Nafion 120).

In the early 1980s Siemens in Germany licensed solid polymer electrolyte fuel cell technology from General Electric (USA)⁴⁹, after it was decided by the German Ministry of Defence that this technology was preferred to alkaline fuel cell technology for submarine application⁵⁰. The chief reasons for this choice were the high power density and absence of corrosive liquid electrolyte. Since then, Siemens has developed high power density solid polymer electrolyte fuel cells of active area 1160-1180 cm² using Nafion 117 and 115 membranes, and also Dow membranes. The Dow membrane produced output power of more than 1 kW per cell, and cell currents up to approximately 2000 A. Overloading capability at double rated current (650 A) was tested for more than 1000 h. Voltage degradation rates of less than 5 µV/h over nearly 20,000 h at rated current density were confirmed for a cell using Nafion 117⁴⁹.

In 1985, funded by the German Navy Procurement Office, Siemens commenced development of a 30-40 kW SPFC module as a component of an AIP power source for the proposed Class 212 submarine^{51,52}. Two laboratory modules were developed, with identical 72 cell stacks using Nafion 117 membrane and with active area 1180 cm², but different degree of auxiliary equipment integration. Module voltage was 52.4 V at a load current of 650 A, producing 34.5 kW. The module was operated briefly for several seconds (time limited by the rate of heat removal) at double rated current, or 55 kW power, with no deleterious effects. The module withstood short circuit currents of approximately 5000 A before dropping to zero within 0.5 seconds as the gas supply automatically shut off. At the rated load, the efficiency was 59% (based on the lower heating value of hydrogen), and 69% at a load factor of 20%⁵². Cell voltage variations were less than ±20 mV/cell.

The Siemens module operates essentially in a "dead ended" mode, with the reactants flowing in a countercurrent cascade through the cells, and only an intermittent purge to remove inert gas components (triggered by a drop in voltage of the last cell) and product water⁵³. The conversion of the reactants is extremely high, and the relative purge gas flow rate (compared with gas consumed in the stack) is less than 0.5% for oxygen (< 30 l/h) and 0.01% for hydrogen (< 10 l/h). There is no need for recirculating gas pumps, only a small cooling water pump, since the high operating efficiency reduces the waste heat. Verification testing of phase 3 prototype modules is expected to be completed at the beginning of 1995.

In 1989 Perry Energy Systems (now Energy Partners) in Florida designed and built a fuel cell system incorporating a Ballard 2 kW SPFC, and installed it in a 2-man submersible (Perry PC1401)⁵⁴. Using compressed gas storage, the endurance of the submersible at maximum propulsion power was increased by a factor of three. The

system performed successfully during 16 test dives at sea. This closed loop fuel cell system, which Energy Partners patented in 1991, was the basis for the design of the AMRL 5 kW system purchased from Energy Partners in 1993, and incorporating Energy Partners proprietary fuel cell stack technology.

The British submarine manufacturer Vickers Shipbuilding and Engineering Ltd. designed a fuel cell powered AIP version (Type 2495) of the Type 2400 (Upholder) submarine^{8,9}. They are collaborating with CJB Developments Limited on systems development, including methanol reformers, using Ballard fuel cell stacks⁵⁵. Since the British decision to sell the Upholders, the VSEL/CJBD emphasis has been on technology demonstration, rather than submarine AIP, and the previous exclusive marketing agreement between VSEL and Ballard for submarine applications has lapsed⁵⁶. This has allowed Howaldtswerke-Deutsche Werft (HDW) of Germany to initiate dialogue with Ballard concerning possible use of Ballard SPFC stacks in their submarine AIP systems⁵⁶.

Ballard was contracted by the Canadian Department of National Defence (DND) to produce a feasibility study incorporating a 300 kW, 100 MWh SPFC system into both an Oberon Class submarine, and a typical modern hull design^{56,57}. A similar contract was placed on Alupower Canada Limited, to assess the aluminium semi-cell technology (see next section). These studies were completed in 1992. The next CAN \$ 9.8M phase, currently underway, is to produce 40 kW demonstrators of both technologies with the evaluations completed by December 1996, and the winner to eventually produce a full-scale 400 kW land based system. The Oberon submarine was chosen for ease of access of data, and to remain impartial to any potential Canadian submarine contenders.

The Ballard AIP feasibility design was based on twenty-two high pressure 15 kW stacks in a 6.0 m plug, using steam reforming of methanol (35 tonnes) for hydrogen production, and supercritical LOX (62 tonnes)^{56,57}. The CO₂ exhaust would be reduced to depth pressure, dissolved in seawater and discharged overboard, thus minimising the parasitic power requirements of an exhaust gas compressor. Ballard had a separate DND contract on methanol reforming, and produced a compact and efficient 10 kW unit known as the Modular Methanol Fuel Processor⁵⁷. Ballard have extensive civilian applications of SPFC technology, and have built a bus in Vancouver which operates on twenty-four 5 kW SPFC stacks, fueled by compressed gaseous hydrogen and an air compressor⁴³. They are collaborating with Daimler-Benz on SPFCs for automobiles, and are also completing a 10 kW natural gas fuelled power generation system⁵⁶.

In June 1991 the US Advanced Research Projects Agency (ARPA) let two parallel contracts to research fuel cells for Unmanned Underwater Vehicle (UUV) or Autonomous Underwater Vehicle (AUV) propulsion⁵⁸. International Fuel Cells Corporation (IFC) was tasked to examine proton exchange membrane fuel cells, and Loral Corporation aluminium-oxygen semi-cells (see Section 4.1.3). After an initial design and demonstration phase lasting 32 months, one company will get the phase 2 contract (14 months) to install the working 15 kW system in the ARPA UUV for sea trials^{59,60}. Initial progress at IFC was reported⁶¹, with details of the 0.28 ft² (0.026 m²) stacks which were fabricated from graphite materials drawn from IFC's commercial

phosphoric acid fuel cell programs. It has been reported⁶² that in 1993 IFC completed two 80 cell SPFC stacks for testing, validation and demonstration. Research is continuing on lithium hydride and sodium chlorate as reactant sources for hydrogen and oxygen respectively, to increase the volumetric energy density.

IFC is also receiving ARPA funding under the Submarine Advanced Energy Technology Program (Subtech) to develop and demonstrate the technology to generate hydrogen from methanol and to supply hydrogen from a regenerable metal hydride bed for use with a SPFC⁶¹. The baseline power system for this design is a 1 MW power plant to be used as an auxiliary power source aboard a nuclear submarine. Hydrogen and oxygen produced by electrolysis (currently used for producing oxygen for crew breathing) using electrical energy supplied by the nuclear reactor, would be stored in metal hydrides and as compressed gas respectively. When required, they would be reacted in the fuel cell. For longer periods of operation the hydrogen would be provided by steam reforming of methanol.

In the former U.S.S.R. solid polymer electrolyte fuel cell power plants of 1 kW power and 50 kWh energy were produced for underwater application⁴⁰, using compressed gases and with a specific energy of 70-80 Wh/kg. A 100 W, 100 kWh plant using chemical storage of hydrogen (NaAlH_4) and oxygen (as a sodium oxide, possibly chlorate) was also created and had a specific energy of 200 Wh/kg, and operated to depths of 120 m. However, current densities in these SPFCs were relatively low at 1 kA/m² (0.1 A/cm²).

Less well documented in the open literature are the AIP submarine developments of the former Soviet navy. However, it has recently been reported⁶³ that a US team sent by the National Science Foundation and Advanced Research Projects Agency to investigate Russian undersea technology visited the Lazurit Central Design Bureau (submarine design). They were reportedly told that the Russians developed a proton exchange membrane fuel cell propulsion system, and installed it in a Whiskey-class diesel-electric submarine which was tested at sea in 1981. There has also been speculation⁶⁴ concerning the nature of the AIP system installed on the Russian research submarine *Beluga*, built in 1987.

4.1.3 Aluminium-Oxygen Fuel Cell

The aluminium - oxygen (Al-O_2) cell is a hybrid battery/fuel cell system and has been variously described as a power cell or a semi-cell. These cells were pioneered in the early 1960s, and much of the research was funded by the US Department of Energy for possible use in electric vehicles²⁵.

There are two types of Al-O_2 fuel cell based on either neutral (saline) electrolyte or concentrated alkaline electrolyte. At lower power levels saline electrolyte is suitable, but at higher power levels such as those required for transportation applications, alkaline electrolyte is required.

The difference between the Al-O₂ fuel cell and an hydrogen-oxygen fuel cell is that the source of fuel is an aluminium anode which is consumed in the process of generating an electrical output and needs to be mechanically replenished. The cathode is inert as in other fuel cells and the oxidant can be either air, oxygen or a hydrogen peroxide solution. Thus the aluminium metal acts as a sacrificial anode in an oxidising environment to produce a useful voltage and current density. The anodic and cathodic reactions are shown in Figure 2, and the theoretical cell voltage is 2.75 volts. However, in practice a cell voltage of 1.6 volts is achieved⁶⁵, twice that of a solid polymer electrolyte fuel cell.

The aluminium anode presents no safety risk as a storage reactant. However, it has a tendency to passivate due to the formation of surface oxide. Independent development of aluminium alloys by Eltech Systems Corporation⁶⁶ and Alcan International⁶⁷ for use in various electrolytes overcame the problem of aluminium passivation, allowing controlled dissolution of the aluminium. Corrosion inhibitors are used to minimize uncontrolled corrosion and evolution of hydrogen, which would decrease the efficiency of the cell. No noble metal catalysts are required to drive the anode reaction. The Al-O₂ fuel cell offers most of the advantages of a low temperature fuel cell, with no requirement to use pure hydrogen, or to reform hydrocarbons.

The high theoretical specific energy of the aluminium anode, 8.1 kWh/kg⁶⁵, causes the oxygen efficiency of the aluminium-oxygen fuel cell to be extremely high. It produces 375 W per standard litre per minute O₂, which is double the value for a hydrogen-oxygen fuel cell (both calculated at 50% efficiency)⁷⁵. The comparison is even more pronounced with heat engines, such as the Stirling engine, which requires on average 5 times more oxygen for the same endurance. This is based on an average Al-O₂ cell voltage of 1.6 V, giving an oxygen consumption of 0.186 kg/kWh, and oxygen consumption figures reported for a number of different Kockums Stirling engines⁶⁸, varying from 0.82 to 1.05 kg/kWh. For an AUV/UUV application, where the volume available for the power plant and reactant storage is very limited, this rate of oxygen consumption severely limits the underwater endurance. At present, the ARPA UUV has a 300 kWh silver-zinc battery contained in a 2.6 m long, 1.1 m diameter subsection, and ARPA's ultimate requirement is for an energy storage of 3.36 MWh (10 kW for 336 hours)⁵⁹. Lee et al.⁶⁹ have performed a detailed study of alternative fuel cells and reactants, semi-cells and batteries. They have shown that the required energy storage can be achieved for energy subsection lengths ranging from 3.3 m (SPFC/chemical hydride/LOX) to 5.3 m (Al semi-cell, 90% hydrogen peroxide), with SPFCs using reformed hydrocarbons and LOX requiring about 4.3 m. In contrast, Kockums has calculated⁷⁰ that for the same UUV using their 4-95 Stirling engine a section length of 3.5 m would be required to store only 600 kWh, and 4.6 m for 1.2 MWh. This will produce significantly lower endurance, for comparable section lengths, and is a direct consequence of the lower efficiency of a heat engine compared to an electrochemical energy converter.

Because of the low requirement of an aluminium-oxygen fuel cell for oxygen, a variety of oxygen sources can be considered, including more expensive ones, such as hydrogen peroxide, chlorates and superoxides. These have particular advantages for autonomous underwater vehicles in some scenarios, such as when an AUV must

remain dormant on station for extended periods of time, and still have adequate energy in reserve for operations when activated. In this situation, the gradual depletion of LOX due to evaporative losses is a liability, whereas chemical storage of oxygen maintains full energy reserves. Hydrogen peroxide is inferior to chlorates and superoxides in volumetric oxygen storage density⁷¹, but as the aluminium - oxygen reaction requires water as a reactant (Figure 2), the use of hydrogen peroxide as the source of both oxygen and water is beneficial.

As discussed above, the specific energy density and specific power density of a particular system will depend on the choice of oxidant and storage. For the aluminium-air system, theoretical values of 400 Wh/kg and 175 W/kg for the alkaline system, and 220 Wh/kg and 30 W/kg for the saline system respectively have been reported⁶⁵.

The chief disadvantage of the system is the requirement for an electrolyte recirculation and processing system. Aluminium hydroxide gel forms within the electrode in saline electrolytes, and must be continuously removed from the cell. In alkaline electrolyte, it is desirable to keep the concentration of the dissolved aluminate reaction product $\text{Al}(\text{OH})_4$ as low as possible, since it has lower conductivity than the original hydroxyl ion. As the aluminate concentration increases, eventually crystalline $\text{Al}(\text{OH})_3$ (hydrargillite) precipitates, regenerating the hydroxyl ion⁷². By removing the precipitated hydroxide from the electrolyte it is possible to maintain constant electrolyte conductivity.

Alupower Canada Ltd is developing three electrolyte management systems for alkaline systems⁵⁶. In the Self-Managed system the electrolyte is contained within the cell, where the hydroxide self-precipitates out and settles at the bottom of the cell. In the Solids-Free or non-precipitating system the hydroxide is kept dissolved in the electrolyte which is pumped to each cell from a common reservoir. In the Solids-Management system, the pumped electrolyte is seeded to actively precipitate the hydroxide, thereby maintaining constant electrolyte conductivity.

In a submarine application, it is necessary to store the hydroxide byproduct, since it cannot be readily dumped overboard without revealing the submarine's location or drastically affecting the submarine's buoyancy. The hydrogen peroxide reactant can be advantageously stored outside the pressure hull in PVC bladders, where it is pressure compensated and reduces the requirement for compensating ballast. It also reduces any safety concerns with storage of hydrogen peroxide inside the pressure hull.

Alupower Canada Limited was granted a contract by the Canadian Defence Department to develop designs for a 300 kW, 100 MWh submarine feasibility study, as previously described⁵⁷. Their system consisted of sixty-four 5 kW stacks in a 6.35 m plug, requiring only 28 tonnes of LOX and 27 tonnes of aluminium, with all by-products contained on board. The recent sale of Alupower Ltd has led to the cessation of further development of the Al-O_2 fuel cell for submarine AIP.

Alupower was also developing several systems for UUVs and AUVs, and this work will continue. These systems include a 2.5 kW, 100 kWh system for the American XP-21

UUV (successfully sea-trialled in November 1993), which achieved an endurance of 48 hours at six knots, or eight times the lead-acid battery endurance⁷³. Alupower has developed a similar system for a Marconi Underwater Systems Ltd UUV in the UK⁵⁶, and a 1.7 kW, 50 kWh system for the Canadian Defence Department's Autonomous Remote Controlled Submersible (ARCS)⁷³. Compressed oxygen is used in the XP-21 and a 50% hydrogen peroxide system as the oxygen source in the ARCS. The endurance of the ARCS power source is expected to be five times that of the Ni-Cd power source, and sea trials were planned to be completed in June 1994. For UUV applications, the gravimetric energy density of Alupower systems are from 6 to 10 times better than lead-acid batteries, and the volumetric energy density 2 to 4 times better⁷³. Energy densities of 267 Wh/kg and 258 Wh/l have been achieved for the Self-Managed system using gaseous oxygen at 4000 psig (27.6 Mpa), and it is considered that a number of improvements could yield an overall two to three-fold increase in the volumetric energy density. Alupower-Chloride, a subsidiary of Alupower Inc. of the US and Chloride Ltd of the UK, has developed aluminium/air Reserve Power Systems in the range 600 W to 6 kW for telecommunication applications^{56,74}.

In the USA, Eltech Research Corporation has demonstrated a 4 kW Al-air fuel cell in a small terrestrial vehicle. It has also provided a 300 W unit to another US company, Aquanautics, researching artificial gill technology to extract oxygen from seawater. Eltech has also developed a conceptual design⁷⁵ for an Al-O₂ fuel cell to power a long-range AUV. As previously mentioned, Loral Corporation was awarded an ARPA contract to research Al-O₂ fuel cells for UUV propulsion. Eltech is a team member and is supplying electrochemical components⁵⁹. It has been reported⁶² that in 1993 Loral began testing short stacks comprising 87 cells. The system uses a pumped potassium hydroxide electrolyte and filter to remove the reaction products.

4.1.4 Direct Fuel Cells

Power generation by the direct electrochemical oxidation of hydrocarbon or hydrogen-containing fuels is highly attractive for transportation applications, since it would remove the need for a separate hydrogen fuel supply or hydrogen generation system.

a. Methanol

Most research has concentrated on the direct methanol fuel cell (DMFC), and Cameron has extensively reviewed the status to 1987⁷⁶ and more recently in 1992⁷⁷. The DMFC can operate using either acid or alkaline electrolytes, but the problem of carbonate buildup in alkaline electrolyte defeats the superior electrochemical performance compared with acid systems. The low catalytic activity for methanol oxidation (three orders of magnitude less than that of hydrogen) requires a large amount of platinum catalyst (up to 1 mg/cm²), highly dispersed over the anode. Poisoning of the catalyst by CO and other reaction intermediates causes high polarisation losses, and current densities are less than 200 mA/cm². Hitachi has marketed DMFCs for low power domestic and leisure uses.

Recent developments include the use of bimetallic or trimetallic catalysts with platinum to reduce the effect of poisoning and enhance the activity. The alloying elements ruthenium and tin are two of many tried that are beneficial, although the mechanism of their promotion is still unclear.

b. Hydrazine

Hydrazine has also been used as a direct liquid fuel (as the hydrate $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$) in alkaline fuel cells, where the electrode polarisation is less than in acid electrolyte fuel cells, and there is no CO_2 byproduct to react with the alkaline electrolyte. However, the high cost of hydrazine relative to hydrogen, and its toxicity, have limited its use to specialist military applications, where size and weight reduction are paramount. The Allis Chalmers 750 W Hydrazine-oxygen fuel cell was mentioned in Section 4.1.

In the late 1960s, Alsthom in France developed hydrazine-hydrogen peroxide systems with power ratings of 1-100 kW⁷⁸. The stacks had very high power density, 1 kW/dm³, corresponding to about 500 W/kg. A 5 kW system was built for subsea application⁷⁹, with the liquid reactants stored in flexible plastic tanks. In pressure testing, the system's power actually increased 36% as the pressure increased to 14 bar, and remained constant to over 50 bar, and performance was unaffected by rapid compression or decompression. In 1970 the system was sea trialled on an SP 350 diving saucer to a depth of 82 meters (limited by the location), and the enhanced performance at depth was verified. However, the maximum efficiency of the non-optimised system was 22%⁸⁰, and the fuel cell stack's useful life at atmospheric pressure was only a few hundred hours, and not determined under pressurised operation.

In 1978-1981 a prototype 3 kW hydrazine-air fuel cell was developed and tested for the Japan Defense Agency⁸¹, to provide non-polluting, silent and portable ac electric power and substitute for conventional engine generators. The prototype met and exceeded all specifications, but the fuel cost was considered to be a possible restriction on successful adoption of the technology.

c. Ammonia

Anhydrous liquid ammonia is easily stored at low pressure, and ammonia vapour can be reacted directly in an alkaline electrolyte fuel cell (but not in an acid fuel cell where it reacts to form ammonium salts). There is significant overvoltage at the ammonia electrode, but current densities of 500 mA/cm² and peak power density of 175 mW/cm² have been reported at a cell temperature of 140°C with 54% KOH electrolyte⁷⁸.

Like hydrazine, ammonia can be easily cracked over catalysts into hydrogen and nitrogen, and used in indirect ammonia fuel cells. Cracked ammonia contains a small amount of residual ammonia, so it is only suitable for use with alkaline electrolytes.

As mentioned in Section 4.1.1, ASEA in Sweden ran alkaline fuel cells on cracked ammonia.

4.2 High Temperature Fuel Cells

In this paper, high temperature fuel cells are described as those where a significant component of the heat requirements of a hydrocarbon reformer can be derived from waste heat from the fuel cell. In some cases, high grade waste heat can also be used to run turbine co-generation units for electricity production in addition to that produced in the fuel cell. The definition of high temperature is somewhat arbitrary in the case of phosphoric acid fuel cells, which fall between the previously described low temperature fuel cells, and the much higher temperature molten carbonate and solid oxide fuel cells.

No high temperature fuel cells have yet been operated on board submarines, and their development has been mainly directed to utility power generation.

4.2.1 Phosphoric Acid Fuel Cell

The phosphoric acid fuel cell (PAFC) was first developed by United Technologies Corporation (UTC) in the USA for operation on primary hydrocarbons such as methane, petroleum products and coal. The oil embargo of the early seventies made many USA electric utilities interested in pursuing PAFC development for central power application.

The most suitable operating temperature is at 190-200 °C, since at lower temperatures the acid is a poor ionic conductor and at higher temperatures material stability of the carbon and platinum components in the cell is limiting. The electrolyte is highly concentrated, so can be very corrosive at higher operating temperatures. There are no water management problems because the water vapor pressure is low, and equilibrium is achieved between the rate of water removal by the reactant gases and the rate of water production.

The utilisation of primary hydrocarbons as the fuel source requires that a steam reformer processing unit be incorporated in the system to convert the primary hydrocarbons into hydrogen and carbon dioxide. As a consequence, the overall efficiency is reduced to 40% for chemical to electrical energy conversion. However, the conversion efficiency of chemical energy to electrical energy plus recoverable heat is near 80%. The heat produced can be used by the reformers in the fuel processing unit, or used for process heat or space heating depending on the application of the fuel cell. External reforming technology has been demonstrated for naphtha and diesel or fuel oils.

Both the anode and cathode consist of platinum electrocatalyst supported on carbon with a fluorocarbon binder. Initially the electrode performance (especially on the cathode) was quite sluggish, and needed to be improved. Major effort in this area brought on the development of appropriate carbon blacks and graphite cell components. These electrode structures now perform satisfactorily up to 40,000 hours. As temperature and pressure increase, corrosion stability becomes a problem, therefore alternative electrocatalysts such as TiC are under examination⁸².

The PAFC is more resistant to CO and CO₂ (which acts as a diluent) contamination than the alkaline fuel cell, however the PAFC only offers average cell efficiency. Operation at elevated temperatures ensures adequate tolerance to small levels of CO from the fuel processor section and provides useful waste heat. Electrolyte starvation in electrodes is a significant cause of observed cell decay, so improved electrolyte management is required with the constant addition of electrolyte to reduce the voltage decay⁸³.

The PAFC technology is the most advanced for terrestrial application (see Table 2). Systems ranging from 1 kW to 11 MW have been designed, built and tested, for both on-site power and heating applications (12.5 kW and 40 kW demonstrations), and for utility power generation (4.5 MW and 11 MW demonstrations)^{24,84,85}.

At present, various American and Japanese utilities are commencing operation of 200 kW units running on reformed natural gas. These are produced by ONSI Corp., a subsidiary of International Fuel Cells (a joint venture between UTC and Toshiba), which has 56 world wide orders for these units, the first being delivered in 1992⁸⁶.

4.2.2 Molten Carbonate Fuel Cell

The molten carbonate fuel cell (MCFC), is a high temperature system regarded as a "second generation" fuel cell because it has not yet reached full developmental maturity.

The operating temperature is about 650 °C and the reaction kinetics are significantly faster than in the lower temperature cells. The electrolyte is a molten salt of equimolar composition of lithium and potassium carbonate which is immobilized in a ceramic matrix tile of lithium aluminate to prevent leakage into the electrode structure. The high temperature is needed for the electrolyte to function in the liquid phase. Useful high grade waste heat generated in the fuel cell can be recovered (for example in a gas turbine) for electricity co-generation.

The high operating temperatures allow in-situ reforming of hydrocarbon fuel such as natural gas (methane) by integration of a carbonaceous fuel processor, giving an overall system electrical efficiency of 50 - 60%. The by-products of the reforming reaction do not poison the cell. CO₂ formed at the anode must be recycled to the cathode to participate in the oxygen reduction reaction, while the CO in the reformatte converts to CO₂ on the anode via the water gas shift reaction, and also by electrochemical oxidation.

The main development problem is that the materials are particularly limiting at these temperatures. Inexpensive nickel or nickel chromium is used for the anode, while the cathode is constructed of nickel oxide which is subject to corrosion problems in the molten carbonate electrolyte. Precipitation of nickel onto the anode, from the dissolution of the conventional nickel oxide cathode in solution, can short circuit the cell and long-term testing of doped lithium iron oxide to replace the cathode is underway to overcome this design problem⁸². It has been suggested that the presence of small amounts of noble metals alloyed with standard materials may enhance the electrode performance in the MCFC⁸⁷.

The MCFC has been under development for about 15 years, particularly in the USA and Japan. Units in the range of 1-100 kW have been evaluated with a scale-up to 1 MW in the next few years. Initially, the fuel will be natural gas, with longer term development to allow integration with coal gasification. The current development status is summarised in Table 2.

4.2.3 Solid Oxide Fuel Cell

The solid oxide fuel cell (SOFC) which is the other "second generation" fuel cell operates at a very high temperature range of 800 - 1000 °C, with electrical efficiencies of 50 to 60%. Because of the extreme temperatures the materials used are confined to ceramics and metal oxides. The system incorporates an yttria-stabilized zirconia solid electrolyte (an oxygen ion conductor). This avoids the electrolyte management problems of liquids and the water management problems of solid polymer electrolytes.

The high operating temperature enables in-situ reforming of hydrocarbons such as natural gas and there is potential for reforming higher hydrocarbons such as naphtha with minimal external pretreatment. The high grade waste heat allows use of co-generation to generate additional electricity by steam or gas turbines, so that the overall conversion efficiency could reach 75 to 80% in a utility power generation system.

The cathode material is a durable metal oxide (strontium-doped lanthanum manganite), and the anode is nickel or nickel cermet. The chief materials problems are high temperature oxidation, inter-diffusion of components, and mismatch of thermal expansion coefficients, which can cause spallation and failure of cell components on temperature cycling.

Many companies have initiated SOFC development programs around the world, including the US and Japan. Westinghouse Electric Corporation has optimised the tubular configuration with a design that has been scaled up to produce 3 kW and 5 kW by electrically linking individual cells through interconnects of doped lanthanum chromite. This design avoids the problem of sealing the individual cells in the stack and has performed successfully for more than 10,000 hrs stable electrical operation⁸⁸ and displayed mechanical stability for more than 30,000 hrs⁸². A variation on the tubular design is the segmented cell-in-series design used by Dornier in Germany^{88,89}.

In 1991, the US Department of Energy (DOE) and Westinghouse commenced a US \$ 140 M program to scale up their current 3 kW and 20 kW designs to build two 25 kW modules, three to five 100 kW modules, and a 2 MW system, with testing of the 25 kW units by Japanese utilities⁸⁶. It has been reported⁹⁰ that Westinghouse has won a US\$7.3M contract administered by NASA for ARPA, to demonstrate a 30 kW transportable solid oxide power generator, for military applications, such as replacing ship service generators on surface combatants, and possibly for running large vehicles. Haldor Topsoe Inc. brings to the team their expertise in steam reforming, since a requirement is to use logistic fuels such as natural gas, diesel oil and JP-4 jet fuel.

Recent developments at Argonne National Laboratories have led to the fabrication of monolithic ceramic electrolyte configurations incorporating thin, strong, tough components with very high area to volume ratios. The honeycomb design is similar to corrugated paperboard and offers very high calculated power densities of about 8 kW/kg or 4 kW/l (fuel cell only)⁹¹.

Planar designs are also under investigation worldwide by a number of laboratories, and in principle allow less stringent manufacturing tolerances, as the individual stack components can be checked before assembly. The power density should also be higher than the tubular design, but high temperature gas seals are required at the edges of the plates^{88,89}. It has been reported that Babcock & Wilcox in the USA is developing a solid oxide fuel cell stack of planar design for UUV and stand-alone power generation applications⁹⁰.

In Australia, a consortium comprising BHP, CSIRO, five state power utilities, the Energy Research and Development Corporation and Victoria's Strategic Industry Research Foundation is developing ceramic fuel cells. The company, Ceramic Fuel Cells Ltd, was established in 1992 and plans to spend AUS \$6 M per year until 1996 on research and development, with the primary focus on large-scale power generation from natural gas⁹². The program relies heavily on the experience built up over a number of years in ceramics research (particularly zirconia ceramics) and catalysis at the CSIRO's Division of Materials Science and Technology in Melbourne.

5. Considerations for Fuel Cell Use in Submarines

Section 2 addressed AIP and submarine operational requirements. The present section will highlight particular properties of fuel cells that make them suitable for submarine AIP, and requirements that will aid in the ranking of the most appropriate fuel cell systems for submarine applications. Figure 4 shows a schematic of the major systems of an integrated low temperature fuel cell system for use in submarine AIP.

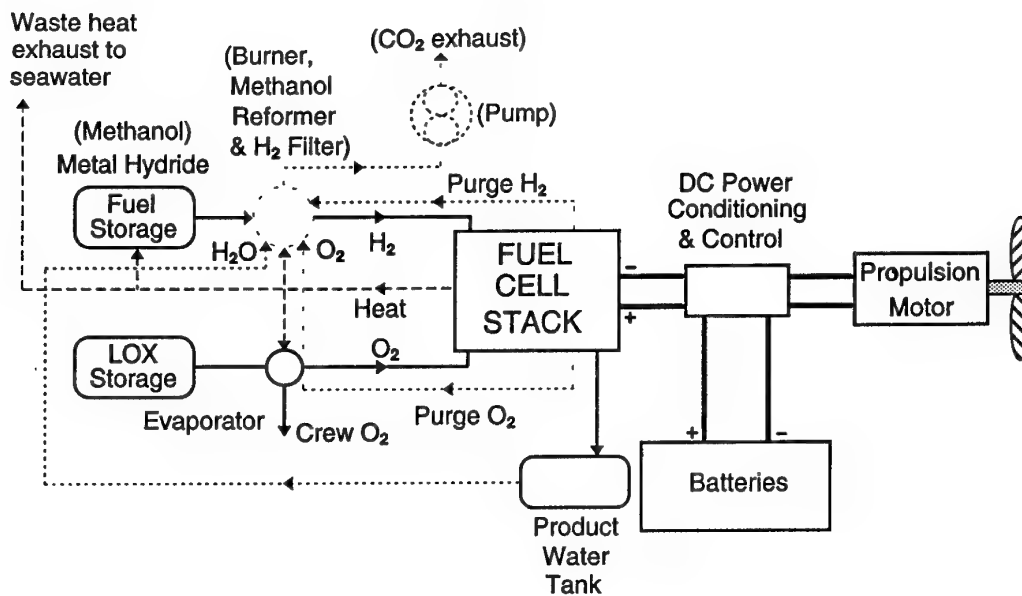


Figure 4: Schematic of Fuel Cell System for Submarine AIP

The waste heat flow from the fuel cell would in practice be achieved with a closed cooling loop, recirculating liquid electrolyte or deionised cooling water through the fuel cell (in the case of AFCs or SPFCs respectively). Heat exchangers would then convey this heat to the appropriate subsystems. If the hydrogen was stored in metal hydrides, then a seawater cooling circuit would provide cooling water to the hydrides while charging them with hydrogen (exothermic reaction), and hot water to desorb the hydrogen (endothermic reaction) while running the fuel cell.

The subsystems and integration required for operation on hydrocarbon fuels (with methanol as an example) are shown by dotted lines. Heat would be supplied for the endothermic steam reforming reaction by burning fuel and the hydrogen purge gases from the fuel cell. Waste heat from the fuel cell can be used to preheat the methanol/water mixture when steam reforming methanol. A filtration or processing unit would be required to separate or render innocuous the reforming byproducts (mainly CO_2 and CO), depending on the type of fuel cell employed. Separation of these byproducts ahead of the fuel cell, by either hydrogen-permeable polymeric membranes or heated palladium-silver diffusion membranes requires a high pressure reformer to overcome the high pressure drop across the membrane, but simplifies the fuel cell system which can then operate at low pressure and in dead-ended mode. If CO_2 is passed through the fuel cell, it must operate in flow-through mode, and with reduced hydrogen utilisation, to prevent polarisation of the anode. With a high pressure reformer, the fuel cell may operate at either high or low pressure. However, if the reformer and/or the fuel cell operates at low pressure, such that CO_2 is exhausted at

low pressure, then a pump would be necessary to dispose of the CO₂ against the seawater pressure. Residual waste heat from the fuel cell or reformer would be used to vaporise oxygen from the liquid oxygen (LOX) tank, to supply oxygen to both the fuel cell and the reformer, and the remaining heat would be exhausted overboard in the seawater cooling water.

5.1 Efficiency and Signature

Fuel cells are highly efficient as chemical energy is directly converted to electrical energy. Fuel cells are not limited by the Carnot cycle, which causes significant thermodynamic heat losses in heat engines. Nevertheless, fuel cells are subject to polarization losses which reduce their efficiency from that theoretically attainable, but the overall system electrical efficiency (40 to 65% depending on type of fuel cell, and whether or not a reformer is used) is still substantially higher than that for heat engines driving generators (30 to 40%).

The efficiency of fuel cells is a maximum at 20 to 40% of full load, and decreases slightly at higher load factors⁹³. This is an advantage if the fuel cell is used to provide both the hotel load and the propulsive load at patrol speeds of 4-5 knots, while floating a fully charged battery. If the fuel cell maximum power is suitably rated, there is capacity for occasional higher patrol speeds without using the battery, or slowly recharging a partially depleted battery without snorkelling. Furthermore, fuel cell efficiency at all load factors is higher than for heat engines. A fuel cell performance goal for submarine applications is a power density of 1 W/cm² of electrode geometric area, for an operating voltage above 0.5V and current density of up to 2 A/cm²⁹⁴.

As mentioned in Section 2.1, a low thermal signature is a desirable attribute for a submarine AIP system and the high efficiencies of fuel cells minimize the amount of waste heat leaving the submarine in the cooling water. Low temperature fuel cells have inherently lower thermal signature than high temperature fuel cells, where effective insulation is required to reduce the heat losses. Use of a reformer with hydrocarbon fuels would impose similar constraints, although the temperature required to reform methanol (between 200 and 250°C⁹⁵) is considerably lower than that of the high temperature fuel cells. Nevertheless, the most efficient reformers are only about 80% efficient, so low temperature fuel cells running on reformed fuel will have a larger thermal signature than those powered by hydrogen, although still much smaller than that produced by heat engines.

Waste products should be disposed of without making the submarine more detectable. A fuel cell running on pure hydrogen and oxygen has only water as the exhaust product and this would be stored onboard for crew requirements. Only minor amounts of hydrogen and oxygen are released if the fuel cell is intermittently purged to remove accumulated impurities from the anode compartments. The hydrogen can either be stored on board (using a suitable metal hydride which requires only a source of cooling water) or catalytically combusted in a controlled manner (e.g. on a catalyst with sufficient oxygen dilution to be below the lower flammability and explosive limits) and the reactant water stored. The purged oxygen can be released to the

submarine atmosphere in a controlled manner to supplement crew requirements when operating for extended periods on AIP. The absence of an exhaust permits running the fuel cell system at the optimum pressure, independent of diving depth.

In the case of a fuel cell system using hydrocarbon fuel, it is necessary to pump overboard the carbon dioxide exhaust products from the fuel reforming, or to store the exhaust products onboard. Since reformers can be operated at high pressure, the CO₂ can be exhausted directly overboard without the need for a separate compressor which would reduce the overall efficiency. For instance, Johnson Matthey methanol reformers for generation of industrial hydrogen operate at 20 bar, producing hydrogen at up to 13 bar by diffusion through silver-palladium membranes⁹⁶. A 20 bar methanol reformer could exhaust CO₂ at depths down to 200 metres. At greater depths a small compressor would be required to provide the increased pressure to exhaust against the seawater pressure. However, reformers can be designed to operate at greater pressures, sufficient for the feasible diving depth of most submarines. The C.D.S.S. CO₂ disposal system was discussed in Section 2.2.

Fuel cells produce direct current and, at fixed load, can be arranged in appropriate series and parallel combinations to match the bus voltage of the submarine battery and the propulsion motor. As there is no need for electrically noisy generators and rectifiers (with time- and space-varying electric and magnetic fields), the electromagnetic signature of a fuel cell AIP system should be less detectable than for heat engine powered electrical generators, which require electromagnetic shielding. If dc to dc inverters are required to boost varying fuel cell output voltage (caused by operation with varying loads) to the battery bus voltage, these could be a source of electromagnetic noise, and would require appropriate shielding. Acoustically, fuel cells are inherently quiet, with no moving parts except for small electric pumps where necessary for liquid electrolyte management (AFC), cooling water, and gas circulation (unless run "dead-ended" as is the Siemens SPFC). Again, the high efficiency of fuel cells means that the amount of cooling water that has to be circulated is appreciably less than that required for a heat engine, so the pump power requirements and noise generated are correspondingly reduced.

5.2 Performance and Reliability

Fuel cell performance depends on the type of fuel cell, the type of fuel and oxidant used, the temperature of the fuel cell and the pressure of the gaseous reactants. Fuel cells undergo a gradual deterioration in output power with time, but high performance over thousands of hours has been demonstrated.

Rapid startup is desirable for an AIP system for a submarine and is a feature of all low temperature fuel cells operating on hydrogen and oxygen. Systems using reformed hydrocarbon fuel would have a longer startup time in order to bring the reformer to operating temperature, but the use of a hydrogen buffer storage (such as compressed gas) would enable a rapid startup. The fuel cell should have good load following characteristics (as should any associated reformer) and be able to handle transient overloads. The efficiency should remain high under partial load.

Acceptable tolerance levels to reformed fuel by-products (such as carbon dioxide and carbon monoxide) is highly desirable, thereby both minimizing the processing equipment required, and extending the lifetime of the fuel cell stack. Stability of electrolytes, including both mechanical strength and low reactivity with other fuel cell components are desirable features of a low maintenance, high reliability fuel cell. Fuel cell stacks and auxiliary systems should be shock resistant for use in a submarine environment.

5.3 Safety and Systems Compatability

Although high pressure compressed hydrogen and liquid hydrogen are routinely and safely used in the chemical process industry and in space research, there is concern about their use within submarines. Hydrogen has lower flammability and explosive limits in air of 4 vol.% and 18 vol.% respectively. The ignition energy for hydrogen is very low, and static discharge is sufficient. The small hydrogen molecule readily leaks from defective pipework, and rapidly diffuses in air. Therefore scrupulous attention must be paid to avoidance of leakage, immediate detection, and failsafe shutdown of hydrogen (and also oxygen) plant.

In the German fuel cell powered submarine *U1*, hydrogen (in metal hydrides) and oxygen (as LOX) were stored external to the pressure hull³⁸, with minimal gas in the pipework within the submarine, and double walled pipes and the fuel cell pressure vessels filled with nitrogen at a higher pressure than the reactant gases, to prevent leaks³⁷. This reduces the hazards, but external storage is not practical for large reactant inventories. Nevertheless, there are alternative forms of storage which generate the hydrogen required by a fuel cell on demand, and these reduce the hazard of uncontrolled venting into the submarine. They are discussed in Section 5.4. It should be noted that conventional diesel-electric submarines routinely generate copious amounts of hydrogen when charging and discharging the lead acid batteries. The hydrogen is monitored and catalytically oxidised in a safe manner to prevent dangerous concentration buildups.

As previously discussed, hydrogen peroxide has advantages when used with aluminium semi-cells. Hydrogen peroxide in concentrated form (70-90%) is known as High Test Peroxide (HTP). It can become violently unstable if contaminated, particularly by organics, and present a major fire hazard. Nevertheless, if suitable system design and operating procedures are implemented, it can be routinely handled with safety. The Swedish, Danish and Norwegian navies have been safely using HTP for around twenty years for torpedo propulsion⁹⁷, and it was used in the British Walter turbine powered experimental submarines, HMS *Explorer* and HMS *Excalibar*⁷. Use of lower concentration, say 50%, and storage outside the pressure hull, would further increase the safety.

The fuel cell system should allow for easy replacement of fuel cell components. The modular design of fuel cells (comprising stacks of fuel cells assembled into modules) facilitates replacement of modules at sea, and readily allows for dimensional changes

to accommodate particular spatial constraints in a submarine. High temperature fuel cells are less versatile than low temperature ones in this regard, since it is necessary to thermally insulate the fuel cell modules. To achieve high volumetric power density with high temperature fuel cells, it is necessary to use modules containing a large number of fuel cells. The dc output of fuel cells is electrically compatible with the submarine battery system, as described previously.

5.4 Reactant Storage and Processing

Submarines are inherently mass and volume limited. Hence, any assessment of the various types of fuel cell systems must also consider the mass and volume of the reactants, and particular storage and processing requirements.

As discussed in Section 2, a submarine of similar size to the Collins Class is required to carry sufficient fuel and oxidant to generate about 100 MWh electrical energy. Since the efficiency of the overall conversion process from the chemical energy of fuel and oxidant to the electrical energy produced in the fuel cell is less than 100%, the quantity of reactants required is proportionately increased. The energy content of the reactants which is of interest for fuel cells is the Gibbs energy or free energy, rather than the enthalpy which is of interest for heat engines.

The possible combinations of fuels and reactants for fuel cells are too extensive to be considered in detail in this paper, and are discussed elsewhere⁷¹. However, the principal findings of this and other reviews of fuel cell reactants⁹⁸ are that oxygen is best carried as cryogenic liquid oxygen (LOX) or hydrogen peroxide (70-80 vol% in water), while the situation for hydrogen is less clearcut.

In order to reduce the on-board inventory of LOX, Kumm⁹⁹ proposed artificial gill technology to extract oxygen from seawater, or from air snorted at periodic intervals. However, extraction of dissolved oxygen from seawater is energy intensive, particularly in tropical waters where the concentration of dissolved oxygen is low⁵. Earlier estimates were that an artificial gill would require about 25% of the energy produced by a fuel cell^{5,100}. However, it has been reported that the power input required to operate an artificial gill system at depths of greater than 100 metres is greater than the power output of the fuel cell that it could support¹⁰¹.

Liquid hydrogen is the most weight efficient mode of hydrogen storage, but presents logistics problems (liquid hydrogen is not produced commercially in Australia). Storage in metal hydrides is considerably safer, but there is a large mass penalty, since most metal hydrides that desorb hydrogen at near ambient temperature contain a maximum of about 2 wt.% hydrogen. Nevertheless, this method has been chosen by the Germans for hydrogen storage in the Class 212 submarine which is proposed will incorporate a SPFC system⁵¹. This follows the successful trial of hydride hydrogen storage, together with LOX, to power alkaline fuel cells on the Type 205 *U1* submarine. Hydrogen storage in hydrides is particularly suited to low temperature fuel cells since the low grade waste heat from the fuel cell may be effectively used to desorb the

hydrogen from the hydride (endothermic process). An additional advantage is that the hydrogen desorbed from hydrides is extremely pure.

Hydrogen may also be derived from hydrocarbon sources by catalytic reforming, either external to the fuel cell (low temperature fuel cells) or internally in high temperature fuel cells (MCFC and SOFC). The reformat gas contains mainly hydrogen and carbon dioxide, with some carbon monoxide. Extensive research is being conducted in this field, especially for transportation applications of low temperature fuel cells which are highly susceptible to poisoning by the CO₂ (AFC) and/or CO (AFC, SPFC) by-products. These must be selectively removed by chemical scrubbing or absorption methods (CO₂) and catalytic water-gas shift reactions and partial oxidation (CO). Methanol is particularly attractive for low temperature fuel cells (and PAFC), since it is easily cracked at relatively low temperatures (200-300°C), and is readily available and easily stored.

In the case of MCFC and SOFC high temperature fuel cells, since they are not prone to poisoning by non-pure gases or CO by-products, internal reforming using the high grade waste heat allows the direct feeding of the reformed gas to the anode for oxidation and reduces the requirement for reforming catalysts. These fuel cells are suited to in-situ reforming of natural gas, but higher hydrocarbons such as naphtha or diesel would probably require some preliminary external reforming before introduction into the stack, to prevent coking (deleterious carbon formation). Desulphurisation beds would be required to prevent poisoning of either the reformer catalyst or the fuel cell.

The chief limitation of externally reforming hydrocarbons is that the net process is energy intensive (endothermic). The PAFC can utilise its waste heat for low temperature cracking of methanol, but reforming of higher hydrocarbons or reforming fuels for use in a low temperature fuel cell (AFC or SPFC) requires some fuel to be burnt to supply the process heat. In addition, as all the reformat hydrogen is not able to be used in the fuel cell, the excess can be burnt to heat the reformer. The best reformers have an efficiency of about 80%, so the overall efficiency of conversion of chemical energy to electrical energy in the combined reformer and fuel cell is reduced compared to the fuel cell alone. For a 60% efficient fuel cell, the overall efficiency (which is the product of the reformer and fuel cell efficiencies) is then about 48%. The increased complexity of the system also leads to reduced reliability and more complex feedback control requirements to match the reformer output to the load-following fuel cell. The reformer also requires a longer startup time from cold, which reduces the advantage of low temperature fuel cells over high temperature fuel cells.

Other considerations such as the effects of reactants and products on the submarine buoyancy, disposal or storage of waste products, safety (flammability, detonability, toxicity), logistics of refuelling and cost of reactants must all be considered in the selection of the best fuel cell/reactants combination. Inevitably, it will be necessary to compromise on some factors, in arriving at the optimum solution.

A study¹⁷ of three different methods of hydrogen storage (metal hydrides, liquid hydrogen and reformed methanol) for the Collins Class submarine showed that all

three options are feasible, based on a nominal 100 MWh (electrical energy equivalent) of fuel cell reactants. The metal hydride option is mass limited, whereas the methanol and liquid hydrogen options are volume limited. The German submarine builder HDW considers that hydrogen storage in metal hydrides is more economic up to a stored energy of about 50 MWh, but a hydrocarbon reformer becomes more economic at higher energies (e.g. 100 MWh)¹⁰².

On the basis of overall system (fuel cell, reformer, reactants) weights and volumes, Kumm^{103,98} calculates that the MCFC operating on desulphurised diesel and LOX is a better choice for a submarine or submersible system than a SPFC fuelled with methanol (reformed externally) and LOX. Nevertheless, Vickers Shipbuilding and Engineering Ltd. (VSEL) and CJB Developments in the U.K. are developing a methanol reforming system to be coupled with a SPFC developed by Ballard Power Systems of Vancouver^{9,104,105}. This was planned to be used for AIP in the Type 2495 submarine^{106,107} but the recent British decision to sell the Upholder Type 2400 submarines makes further development for this class of submarine unlikely⁵⁶, and the work is now directed at general applications.

6. Assessment of Fuel Cell Systems Against Submarine Requirements

Candidate fuel cell systems for submarine applications must be assessed against the criteria discussed in Sections 2 and 5: efficiency, signature, performance, reliability, safety, systems compatibility and logistics and costs. Each of these criteria may be given a weighting, based on its relative importance for a particular application, and the sum used to rank the fuel cell systems in order of preference.

Such an approach has been used by Arctic Energies Ltd. in the USA for evaluation of power sources for autonomous underwater vehicles and submersibles^{103,108}. This approach has also been applied to fuel cell powered submarines^{98, 99} and is the most detailed assessment to date. While the results of such an evaluation are obviously dependent on the weightings applied to the different variables, the methodology can be readily adapted to changing scenarios.

There have been a number of other assessments of different types of fuel cells for marine applications including submarines^{7, 33, 109, 110} and submersibles, and autonomous or unmanned underwater vehicles^{69, 80}. These assessments vary in their extent and are less formalised than the methodology used by Kumm, but nonetheless offer valuable insights.

It is not possible in the scope of the present paper to offer a rigorous comparison of all the pertinent factors in arriving at the optimum fuel cell for submarine AIP, particularly as some systems (SPFC, MCFC, SOFC and aluminium semi-cell) are still at a relatively early stage of development. However, it is possible to make some general

comments indicating those factors considered of primary importance in assessing fuel cell types against the submarine requirements.

6.1 High Temperature Fuel Cells

High temperature fuel cells (and indeed any form of high temperature heat engine) are considered to be undesirable for submarine AIP, because of the difficulties of thermal management in the confines of a submarine, where crew comfort is of great importance for effective performance over long periods of submerged patrol. While use of appropriate thermal insulation and increased air conditioning will contain the problem, the penalty is increased bulk (due to the volume of insulation) and hotel power requirement. This decreases the power available for propulsion or battery recharging, and reduces the underwater endurance for a particular quantity of reactants. The importance of reducing the hotel load, which dominates the propulsion load at patrol speeds (4-5 knots), has recently been highlighted¹¹¹. Slow startup, which could be several hours for an initially cold system, makes high temperature fuel cells unsuitable for submarine use. Materials problems may be induced by cycling the temperature of a high temperature fuel cell between high and low temperatures over a number of operating cycles. Even if the fuel cell is maintained at an elevated temperature when on standby, to minimise thermal and mechanical stresses on components, there will be an energy penalty to do this.

Safety is also potentially compromised through use of a high temperature system in a submarine, since fires may be initiated by a hot ignition source, or water ingress may cause a catastrophic steam explosion.

For these reasons, as well as their relatively early state of development, the molten carbonate and solid oxide fuel cells are not viewed as serious contenders for submarine AIP at the present time, despite their potential long term attractiveness for in-situ reforming of diesel fuel. It is considered that these systems are much more suited to future naval surface vessel electric propulsion, where there are not the same constraints as on a submarine, and the increased efficiency using electricity co-generation could be fully utilised. Furthermore, these systems are best suited to high power (multi megawatt) generation rather than the low power requirements of a submarine AIP system. This is tacitly recognised by Kumm⁹⁹ who proposes that a "militarily credible" fuel cell propelled submarine would require a 4 MW power plant and an endurance of 3200 MWh. Such a submarine would have all the diesel-electric plant and 3/4 of the battery bank replaced by fuel cells (MCFC). This takes the concept of submarine AIP beyond the hybrid configuration envisaged for retrofit of the Collins Class, and at the present state of development of fuel cell technology is considered excessively high risk and expensive.

Phosphoric acid fuel cells are judged unsuitable primarily because of their low efficiency, low power density and electrolyte corrosion problems.

6.2 Low Temperature Fuel Cells

Low temperature fuel cell systems are considered best suited for AIP applications, for the reasons given above, as well as reduced startup time and thermal signature. Of the low temperature fuel cells, there are only two which are presently proved capable of attaining high power densities, these being the alkaline and solid polymer electrolyte fuel cells. The aluminium-oxygen semi-cell has not yet demonstrated sustained high power densities (with an alkaline electrolyte) with effective removal of the aluminium hydroxide byproduct, although Alupower is making considerable progress and this situation is likely to change. The refuelling logistics are also more difficult with a solid fuel than a liquid fuel.

In principle, using a source of high purity hydrogen stored as either liquid hydrogen or in a metal hydride, both AFC and SPFC are equally well suited for submarine AIP. The water management requirements for SPFC are matched by the electrolyte management requirements of the AFC. Although the AFC has a higher cell voltage than the SPFC, the higher current densities in the latter (using the recent high performance membranes) produce a higher power density per unit volume and weight. It is noteworthy that despite the successful demonstration of alkaline fuel cells in the Type 205 submarine *U1*, the German Ministry of Defence directed that Siemens develop the solid polymer electrolyte fuel cell for submarine applications.

The chief disadvantage of the alkaline fuel cell is the requirement to remove all CO₂ from the hydrogen if reformed hydrocarbons are used as the fuel, and all CO₂ from the air if the fuel cell is to be capable of operation on air while the submarine is snorting. (Such a capability was proposed by VSEL for the Type 2495, which would confer the advantage of quiet snorting in some circumstances where it was desirable to minimise the use of LOX, but also avoid the noise and heat signature of diesel operation). While CO₂ removal is possible by a number of methods, these place an energy penalty on an AFC system that is not present for the CO₂ tolerant SPFC system, which has a mechanically and chemically stable solid electrolyte.

Nevertheless, if non-hydrocarbon fuels such as ammonia are used, the alkaline fuel cell has advantages over an SPFC operating on reformed methanol. Slight ammonia carryover from the reforming unit is not detrimental to an AFC, whereas it is to an acidic SPFC, which would require additional gas purification. However, ammonia is more difficult to handle than methanol, and more toxic (the inhalation exposure standards are 25 ppm for ammonia, 200 ppm for methanol), so it would be unlikely to be acceptable as a submarine AIP fuel. Although less flammable than methanol, ammonia can form explosive mixtures with air (range 16%-25% ammonia).

For the above reasons, it is believed that the SPFC is more suited for submarine AIP than the AFC at the present time, irrespective of whether pure hydrogen or reformed hydrogen is used to fuel the fuel cell. Unless significant research and development, similar to that currently occurring in the SPFC field, is resumed in the AFC field, it is unlikely that developments will occur which will necessitate a reassessment of this view.

Use of an external hydrocarbon reformer on a low temperature fuel cell somewhat diminishes the advantages of low temperature operation, due to the reduction in overall system efficiency, the increased complexity, and slower response to load variations. Methanol is the most easily reformed hydrocarbon, requiring only relatively low reformer temperature, but introduces problems of toxicity and flammability. Fuel logistics and safety considerations would favour the use of reformed diesel, but the higher temperatures required are less compatible with the use of low temperature fuel cells. Unless significant developments occur in metal hydrides, the choice between metal hydrides and methanol reforming will continue to be difficult, and rather dependent on the tolerable increase in submarine length for a particular AIP endurance. Where allowable, metal hydrides are favoured over methanol reforming, for their system simplicity, favourable thermal signature, and safety. However, on a large submarine such as Collins, with large AIP endurance requirements, the shorter plug length afforded by methanol reforming is likely to override the disadvantages of a less efficient and more complex system, with greater safety issues.

7. Conclusions

Six different types of fuel cells were compared including the solid polymer, alkaline, phosphoric acid, aluminium-oxygen, molten carbonate and solid oxide. After considering a wide range of factors, the solid polymer electrolyte fuel cell (SPFC) or proton exchange membrane fuel cell (PEMFC) was identified as the most suitable type of fuel cell for use in submarine air independent propulsion. Its advantages in comparison to other fuel cell systems include low temperature operation, cold start ability, high power density, solid electrolyte, mechanical and chemical stability, and low maintenance.

Studies by other countries have come to similar conclusions, and this type of fuel cell was selected by British and German submarine manufacturers for the designs for the Type 2495 and Class 212 submarines respectively, and is under active consideration by the Canadian Department of Defence for its possible Oberon replacement submarine program. It has recently been reported¹¹² that the German MOD has notified Parliament that it is planning to place a DM 2.6 billion contract for the first batch of four Class 212 submarines in 1995, with the funding to be spread between 1997-2007. It is unlikely that other types of fuel cells will be considered in the next decade for submarine air independent propulsion, given the long lead times in developing new technology.

It has been emphasised that selection of the most suitable fuel cell system for submarine AIP also involves consideration of the reactant storage and processing, particularly for the fuel. The best reactant storage/processing system may vary with the particular application and strategic scenario. Thus, metal hydride hydrogen storage is ideal for a simple system with maximum efficiency and minimal thermal signature. However, it is relatively limited in endurance, and for very long endurance patrols, as

might be required for the Collins Class, it might be preferable to adopt the more complex and less efficient system of methanol reforming.

The selection of a high power density fuel cell system for submarine air independent propulsion will permit enhanced underwater range and endurance, and minimum indiscretion ratio and thermal signature, superior to that obtainable from any heat engine. This will greatly extend the strategic advantage of the Collins Class submarines, and preserve their technological edge over other conventional diesel-electric submarines in their theatre of operations. Whether or not Australia chooses to adopt AIP technology will depend on a number of factors, chiefly strategic, political and economic. This paper has highlighted the technological issues that must be addressed if an informed decision is to be made regarding fuel cell technology. Future papers will focus on the comparative aspects of different AIP technologies.

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AUTHOR(S)
Peter L. Mart and Jenny MargeridisCORPORATE AUTHOR
DSTO Aeronautical and Maritime Research Laboratory
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ABSTRACT

Conventional diesel-electric submarines must surface periodically to recharge their batteries by using generators driven by air breathing diesel engines. During this time, submarines are most vulnerable to detection. Air independent propulsion (AIP) systems are being developed that will generate electrical power while the submarine is submerged. Such systems provide power for recharging the batteries, for propulsion and for the submarine's other electrical equipment requirements, while the submarine is submerged. Fuel cells, one of the leading AIP contenders, are electrochemical energy converters that enable the chemical energy of a stored fuel and an oxidant to be converted directly to electricity.

This report reviews the main operational requirements of AIP systems in diesel-electric submarines, with the main objective of surveying the various types of fuel cell systems and ranking them in order of suitability for possible future use as AIP systems in the COLLINS Class submarine. Descriptions are given of the six fuel cell types currently in use or under development for terrestrial power generation, but particular attention is given to those systems that are in use or have the greatest potential for sub-sea applications.

The particular advantages of fuel cells compared with heat engines are highlighted, as well as the limitations imposed by fuel requirements. It is emphasised that for submarine AIP applications, there is no single optimum selection of fuel cell system, or of the fuel and oxidant and their associated storage and reactant processing systems. Each submarine application must be assessed on the basis of a number of different, and sometimes competing, criteria which will be weighted differently for different applications and strategic scenarios. It is concluded, however, that low temperature fuel cells are generally better suited for submarine applications, with the solid polymer electrolyte fuel cell having particular advantages.

Fuel Cell Air Independent Propulsion of Submarines

Peter L. Mart and Jenny Margeridis

(DSTO-GD-0042)

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